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MATERIALS OF MACHINES

BY

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PREFACE TO SECOND EDITION

THE object of this book is to supply elementary knowledge of metallic materials used in the construction and operation of machines. The aim has been to bring together a group of correlated facts, to state them clearly and to show their relation.

The book is in two parts: the first part deals with the *manufacture* of materials; and the second deals with the *properties* of materials. Understanding of the first part is believed to be an essential preliminary to the study of the second part, while understanding of the second part is very desirable for those who design, construct and operate machines.

The writer wishes to express his great obligation to Professor Herman Diederichs for his ever-ready and efficient help on part first, to Professor George B. Upton whose researches and kind suggestions made it possible to present part second in its present form, and to Professor Heinrich Ries for his kindness in criticizing the chapter on Refractory Materials.

Those who wish to follow part second with a fuller and more scientific treatment are referred to Professor Upton's forth-coming book on " Materials of Construction."

A. W. S.

ITHACA, *July* 1914.

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MATERIALS OF MACHINES

PART FIRST—MANUFACTURE

CHAPTER I

PRELIMINARY CONSIDERATION OF FUELS

In general, a fuel is a substance which evolves heat while uniting chemically with oxygen. The fuels ordinarily used, however, depend for their value upon the presence of carbon or hydrogen. A fuel may be pure carbon (solid), pure hydrogen (gas) or combinations of carbon and hydrogen like petroleum (liquid). Fuel may, therefore, be solid, liquid or gaseous.

All industrial fuels have their origin in plant growth. A growing plant, because of energy received from the sun's rays, separates carbon dioxide of the atmosphere into its constituents, releasing the oxygen and storing the carbon within the growing plant tissue; it also stores hydrogen and oxygen derived from the sap so that the resulting plant fiber, wood or stems or leaves or grasses, consists of a combination of carbon, hydrogen and oxygen.

Wood may be used directly as fuel or may be converted into charcoal. Nature's processes, acting through long periods of time, have converted plant fiber into coal or petroleum or natural gas; and artificial processes produce fuel gas and coke from coal, and produce fuel gas from petroleum. Hence, the potential heat energy of fuels is

really energy which came from the sun and was stored through the agency of plant growth.

The expression "complete combustion" means the combination of a fuel element with that amount of oxygen which produces the most stable compound. Thus, complete combustion of carbon produces carbon dioxide, CO_2; and complete combustion of hydrogen produces water, H_2O.

Combustion of unit weight of any fuel produces a definite quantity of heat which is called its **calorific power.** Since this is a quantity of heat, it is expressed in units of heat quantity; in this case British thermal units.*

When carbon is burned with restricted oxygen supply, the gas carbon monoxide, CO, is formed. Under proper conditions of temperature and with adequate oxygen supply, this carbon monoxide unites with more oxygen forming carbon dioxide, CO_2, and evolving heat. Hence carbon monoxide is a gas fuel.

Calorific powers of combustibles from experimental determinations are as follows:

Combustible	Calorific power
Carbon burned to carbon dioxide (CO_2)	14,540 B.t.u.
Carbon burned to carbon monoxide (CO)	4,500 B.t.u.
Carbon monoxide burned to carbon dioxide (CO_2)	4,300 B.t.u.
Hydrogen burned to water (H_2O)	62,100 B.t.u.
Marsh gas burned to carbon dioxide (CO_2) and water (H_2O)	23,500 † B.t.u.

* A British thermal unit (abbreviation, B.t.u.) is the quantity of heat necessary to raise the temperature of one pound of water from 32° F. to 212° F., divided by 180. This gives the average quantity of heat per degree for the specified temperature limits.

† Since one pound of marsh gas is composed of three-fourths pound of carbon and one-fourth pound of hydrogen, it would seem that its calorific power should be equal to $\frac{3}{4} \times 14{,}540 + \frac{1}{4} \times 62{,}100 = 26{,}430$ B.t.u. instead of 23,500 B.t.u. The difference, 2930 B.t.u., is energy used in separating the carbon and hydrogen of the marsh gas.

The calorific power of carbon monoxide burned to carbon dioxide may be derived from the calorific powers of carbon burned to carbon monoxide and carbon burned to carbon dioxide as follows:

The carbon in one pound of CO equals, from the relation of atomic weights, $\frac{12}{28} = \frac{3}{7}$ pound. In burning to CO, this $\frac{3}{7}$ pound carbon evolved heat $= 4500 \times \frac{3}{7} = 1928$ B.t.u. If it had been burned to CO_2, the heat evolved would have equaled $14{,}540 \times \frac{3}{7} = 6231$ B.t.u. The difference between these two heat quantities equals the heat that would be evolved by burning carbon monoxide to carbon dioxide. This equals $6231 - 1928 = 4303$ B.t.u. This value checks closely with values derived from experiment.

Temperatures resulting from combustion. — When a combustible is burned and the heat evolved is applied exclusively to the products of combustion, the temperature attained depends on the following factors:

1. The calorific power of the combustible.
2. The nature, relative weights and the specific heats of the products of combustion.
3. The quantity of air supplied.
4. The temperature before combustion of the fuel and the air that supplies oxygen for the combustion.

Factor 1 is a measure of the quantity of heat that is available for application to the combustion products, and with a given quantity of a given material to heat, the resulting temperature is proportional to the quantity of heat available.

2. The temperature of combustion depends on the nature of the combustion products; this may be illustrated as follows: If the fuel is hydrogen, the combustion product

is water; the water must be vaporized, and the heat of vaporization becomes latent and hence cannot affect temperature. This is, of course, not true when there is no change of state of combustion product as in case of carbon burned to carbon dioxide. It is obvious that with a given quantity of heat available, the temperature increase depends upon the weight of substance heated, and upon the quantity of heat that will raise unit weight of the substance through a temperature range of one degree; that is, upon its specific heat.

3. This factor affects the result because any excess of air increases the weight of matter to be heated by a given heat quantity with corresponding reduction of temperature.

4. This factor affects the result because with 1, 2 and 3 specified the products of combustion would be raised in temperature through a certain **range** and the **final** temperature would depend on the temperature of the substance when heating began.

To find the temperature produced by complete combustion of pure carbon without excess of air.—Chemically the combustion may be represented as follows:

$$\begin{matrix} 24 & 64 & & 88 \\ C_2 & + & 2\,O_2 & = & 2\,CO_2. \end{matrix}$$

The relative weights appear above the symbols. For every 24 weight units of carbon 64 weight units of oxygen must be supplied; hence for one weight unit of carbon $\frac{64}{24}$ weight units of oxygen must be supplied. But the oxygen is supplied from the air, which is a mixture of oxygen and nitrogen with very small amounts of water vapor, carbon dioxide and other gases. For the present purpose all may be disregarded except nitrogen and oxygen which are present with close approximation as follows: nitrogen 77 per cent by weight and oxygen 23 per cent by weight.

Hence, to supply 23 weight units of oxygen, 100 weight units of air are necessary; therefore, it takes $\frac{100}{23}$ weight units of air to supply one weight unit of oxygen. Hence, for complete combustion of one pound of pure carbon the weight of air required equals

$$\frac{64}{24} \times \frac{100}{23} = 11.6 \text{ pounds.}$$

The resulting gases, when combustion is complete, are nitrogen and carbon dioxide. The nitrogen takes no part in the combustion and the weight is 77 per cent of the air supplied or 11.6 pounds $\times$ 0.77 = 8.93 pounds. For every pound of carbon (see equation above) $\frac{88}{24}$ = 3.66 pounds of carbon dioxide are produced.

Summary. — One pound carbon (solid) burned in 11.6 pounds air (gas) produces 8.93 pounds nitrogen (gas), and 3.66 pounds carbon dioxide (gas).

Heat changes during this combustion. — Assume that the air supplied and the carbon are at a temperature of 65° F. before combustion. Then, taking 0° F. as the heat datum, or temperature at which heat begins to be considered, the air would bring to the combustion 11.6 $\times$ 65 $\times$ 0.237 = 178.7 B.t.u. in which 11.6 is the weight of air, 65 is the temperature range above the heat datum, and 0.237 is the specific heat of air at constant atmospheric pressure and at a temperature of 65° F. The heat that one pound of carbon would bring to the combustion equals 1 $\times$ 65 $\times$ 0.24 = 156.6 B.t.u. The complete combustion of the carbon would evolve 14,540 B.t.u. Hence, the total heat available to raise the temperature of the products of combustion above 0° F. equals 14,540 + 178.7 + 15.6 = 14,734 B.t.u.

This heat would raise 8.93 pounds nitrogen and 3.66 pounds oxygen to some temperature, t°, to be determined.

The mean specific heat of nitrogen, with the temper-

ature range 0° to 4000° F., is 0.2848 * and of carbon dioxide for the same range is 0.2867.*

The heat absorbed by the nitrogen while its temperature is raised to $t°$ F. equals $8.93 \times t \times 0.2848 = 2.543\,t$; the heat absorbed by the carbon dioxide while its temperature is raised to $t°$ F. equals $3.66 \times t \times 0.2867 = 1.049\,t$ B.t.u.

Hence $t\,(2.543 + 1.049) = 14{,}734,$
whence $t° = 4100°$ F.

The temperature produced by burning carbon monoxide gas may be found by the same method. This chemical combination is represented thus;

$$\begin{matrix} 56 & 32 & 88 \\ 2\,CO + & O_2 = & 2\,CO_2. \end{matrix}$$

The weight of air per pound of carbon monoxide equals $\frac{32}{56} \times \frac{100}{23} = 2.48$ pounds. Of this air 77 per cent, or 1.9 pounds is nitrogen; the resulting carbon dioxide equals $\frac{56}{88} = 1.57$ pounds.

Summary.—One pound carbon monoxide (gas) burned in 2.48 pounds air (gas) produces 1.9 pounds nitrogen (gas) and 1.57 pounds carbon dioxide (gas).

As before, assume 0° F. as a heat datum, and 65° F. as the temperature of the fuel and air supply before combustion. Then the air would bring to the combustion $2.48 \times 65 \times 0.237 = 38.2$ B.t.u. and the fuel would bring $1 \times 65 \times 0.245 = 15.9$ B.t.u. The heat evolved by the combustion (calorific power of the carbon monoxide) = 4300 B.t.u. Hence, the total heat available to raise the temperature of the products of combustion above 0° F. $= 4300 + 38.2 + 15.9 = 4354$ B.t.u.

* See "Experimental Engineering," Carpenter and Diederichs, page 865.

The mean specific heat of nitrogen (0° to 4000° F.) = 0.2848, and of carbon dioxide = 0.2867.

$$\text{Then } t = \frac{4354}{(1.9 \times 0.2848) + (1.57 \times 0.2867)} = 4397° \text{ F.}$$

The temperature produced by the combustion of hydrogen may also be found: The combustion is represented chemically as follows:

$$\begin{matrix} 4 & 32 & 36 \\ 2\,H_2 + O_2 = & 2\,H_2O. & \end{matrix}$$

For every weight unit of hydrogen 8 weight units of oxygen must be supplied, and the corresponding weight of air $= \frac{100}{23} \times 8 = 34.8$ pounds. Hence, the combustion of one pound of hydrogen requires 34.8 pounds of air, of which 77 per cent, or 26.8 pounds, is nitrogen. The water resulting from the combustion $= \frac{36}{4} = 9$ pounds.

Summary. — One pound hydrogen (gas) burned in 34.8 pounds air (gas) produces 26.8 pounds nitrogen (gas) and 9 pounds water (superheated vapor).

The water produced is raised in temperature to 212° F.* and converted into steam which is superheated to the temperature resulting from the combustion.

The specific heat of hydrogen at 65° F.	= 3.37.
The specific heat of air at 65° F.	= 0.237.
The specific heat of water at 65° F.	= 1.00.
The mean specific heat of nitrogen from 0° F. to 4000° F.	= 0.2848
The mean specific heat of steam from 212° F. to 4000° F.	= 0.6724.

The heat that is available to raise the temperature of the products of combustion may be found as follows:

With 0° F. for a heat datum, and with 65° F. as the temperature of the hydrogen and air before combustion, one

* Assuming the combustion to occur at atmospheric pressure.

pound of hydrogen would bring heat to the combustion equal to $1 \times 65 \times 3.37 = 219$ B.t.u. The air would bring heat equal to $34.8 \times 65 \times 0.237 = 536$ B.t.u.; the heat evolved by the combustion (calorific power of hydrogen) = 62,100 B.t.u. The sum of these values = 62,755 B.t.u. This heat, however, cannot all be applied to raise the temperature of the products of combustion, because the heat applied to vaporize the water does not affect temperature. This heat = 970* × 9 = 8,730 B.t.u. Hence, the heat that really does affect temperature equals 62,755 − 8730 = 54,025 B.t.u. This heat raises the temperature of 9 pounds of water from 65° F. to 212° F.; it also raises the temperature of 9 pounds of steam from 212° F. to $t°$, the final temperature; it also raises the temperature of 26.8 pounds of nitrogen from 65° F. to $t°$. Hence, the following equation may be written:

$$54{,}025 = (212 - 65)\,9 + (t - 212)\,(9 \times 0.672) + (t - 65)\,(26.8 \times 0.2848).$$

Hence $13.68\,t = 54{,}025 + 1282.6 + 495.95 - 1323$

and $$t = \frac{54{,}480}{13.68} = 3982° \text{ F.}$$

For the assumed conditions, then, the theoretical temperatures produced by complete combustion are: for carbon 4100° F.; for carbon monoxide 4397° F.; and for hydrogen 3982° F.

It may seem strange that the combustion of carbon monoxide — which is partially burned carbon — should produce a higher temperature than the combustion of the original carbon; especially in view of the fact that the calorific power, or heat produced per pound, is 14,540 B.t.u. for carbon, and only 4320 B.t.u. for carbon monoxide. Inspection of the illustrative examples given above, how-

* The heat of evaporation of steam at atmospheric pressure.

ever, shows that while the heat evolved in the case of carbon monoxide is less, the weight of the products of combustion is less in greater proportion, and hence the resulting temperature is higher.

The reasons why hydrogen, with its high calorific power, produces a temperature lower than either of the other fuels, are the greater relative weights of the substances heated, their greater heat capacity, and the absorption of heat for the vaporization of the water produced by the combustion with no resulting change of temperature.

The theoretical temperatures found are never attained in actual combustion for the following reasons:

1. Combustion is seldom complete; finely divided solid fuel falls through grates, and carbon monoxide and marsh gas often escape unburned to the stack, because of low temperature or insufficient oxygen supply; hence, the theoretical quantity of heat to raise the temperature is not completely evolved.

2. In practice an excess of air is always supplied in the effort to prevent incomplete combustion, and this increases the weight of the gas to be heated and thus reduces the resulting temperature. For example, the temperature resulting from the complete combustion of carbon, with conditions as in the example on page 4 and with 50 per cent excess of air, is about 3000° F. instead of 4100° F. with no air excess; with 100 per cent excess the theoretical temperature is about 2300° F.

3. There are always radiation losses, which increase very rapidly with increase of temperature; while these losses may be much reduced by careful design and construction, and by the use of heat insulating materials, they cannot be reduced to zero.

4. Moisture, which is usually present in the fuel and in the air supply, absorbs heat while it is heated, vaporized

and superheated, and this heat is taken away from the heat that is available to raise temperature.

5. There is also a limit due to the fact that at high temperatures dissociation of the products of combustion may occur; this may be explained as follows:

In a space like an ordinary furnace containing carbon, oxygen, carbon monoxide and carbon dioxide, there are probably two coexisting tendencies; one for carbon and oxygen to unite, and another for the combinations of carbon and oxygen to separate. At a given temperature these tendencies will be in equilibrium when a certain proportion exists among the substances present. As the temperature changes, however, the proportions corresponding to equilibrium change. When temperature rises in a space containing the substances specified above in equilibrium, some of the carbon dioxide will dissociate in order to restore the disturbed equilibrium. This dissociation is accompanied by absorption of heat which tends to check the rise in temperature and, therefore, **to limit the temperature of combustion by the dissociation of combustion products.**

It is impossible in the present state of knowledge to state the proportions and temperatures quantitatively, but it is certain that in ordinary furnaces burning carbon fuel a temperature of 3000° F. can be produced, while it is probable that dissociation of CO_2 would prevent the temperature rising much above 3500° F.

Similarly, highly superheated steam from the combustion of hydrogen would dissociate with rising temperature to restore equilibrium and would thus limit the temperature of combustion of hydrogen to some value less than the theoretical value derived above.

In engineering and metallurgical processes it is often required to produce temperatures higher than 3000° F.

while guarding against incomplete combustion of carbon with a 50 per cent (or greater) excess of air, or while using a gas fuel diluted with a large proportion of nitrogen. This can be accomplished, up to the limit set by dissociation, by preheating the air supply, and the fuel also, if it is gas or vapor.

With the method of computation used above it is found that in case of complete combustion of carbon with 50 per cent excess of air, the preheating of the air supply to 1200° F. increases the temperature of combustion from about 3000° F. to about 3900° F.; while with 100 per cent air excess and preheating to 1200° F. the theoretical temperature is about 3300° F. If the preheating is increased to 1500° F. with 50 per cent air excess, the resulting theoretical temperature becomes 4200° F., and with 100 per cent air excess it becomes 3600° F. Of course, these values would be somewhat reduced by radiation loss. Since dissociation (see page 10) sets a probable limit at about 3500° F. it would seem, from the theoretical temperatures just given, that preheating of air to produce high final temperature might be overdone.

If pure oxygen were used instead of air for the support of combustion of carbon, the resulting theoretical temperatures would be higher, since there would be no nitrogen to heat. This temperature cannot be computed because of the uncertainty as to the value of the specific heat of carbon dioxide at very high temperatures. But in this case, as in those previously considered, the dissociation limit would be met, though its value might be changed because of the different composition of the products of combustion.

It follows that if temperatures much above 3500° F. are required, they must be produced by other means than the burning of carbon fuel.

There are many other substances in nature which, when they combine with oxygen, produce temperatures higher than those that result from the burning of carbon or hydrogen. Two such substances, silicon and aluminum, will be briefly considered for illustration.

Silicon. — In the Bessemer process,* silicon, which constitutes only from 2 to 5 per cent of the charge at the beginning of the "blow," is burned to silica, SiO_2, and chiefly as a result of the heat thus evolved, the entire charge is raised in temperature from about 2500° F. to about 3500° F., at which the nearly pure iron is held in a fluid state. Obviously, if the silicon were present in larger proportion, its burning would produce a higher temperature, if the temperature were not reached at which vaporization of the silica or the iron would establish a temperature limit.

Aluminum. — Finely divided aluminum and iron oxide are intimately mixed, the mixture being called "thermit," and when this mixture is ignited the oxygen of the iron oxide goes over to the aluminum, forming alumina, Al_2O_3, and leaving pure iron. The chemical changes occur rapidly and very vigorously and the resulting temperature is said to be about 5000° F. At this temperature the alumina may be drawn off as a molten slag leaving the pure iron in a very fluid state. Sometimes the product of this process is used to mend cracked castings. The hot liquid iron from the process is allowed to run into the space between the cracked surfaces, the metal of these surfaces is melted, the space is filled with molten iron, which cools and solidifies, and the cracked surfaces are joined.

This process is also applied to the production of metals like tungsten and chromium, in a very pure state, from

* See page 60.

their oxides. The metallic oxide is mixed with pure aluminum, both finely divided, and the mixture is ignited; the products are pure metal and aluminum oxide, the latter being removed as slag.

The use of aluminum as a fuel is only justified by the production of exceptional results, because the fuel must be produced by an artificial and costly process.

Nature does not produce silicon and aluminum fuel; nature's processes have produced vast quantities of silica, SiO_2, and alumina, Al_2O_3, in which the combination with oxygen and evolution of heat has already occurred; that is, they are fuels that have been burned. This is true of almost all substances that might be used as fuel; in fact, it is true of carbon and hydrogen which occur in nature combined with oxygen as carbon dioxide, mechanically mixed with the air, and as water in its well-known distribution. But the energy of the sun's rays through the agency of plant growth is continually pulling away carbon from the oxygen of the carbon dioxide of the air and storing it with hydrogen and oxygen from the sap in the products of plant growth. In the past, these have been converted by nature's processes into coal, petroleum and natural gas and stored underground.

Solid fuels may be classified as:

(*a*) Raw fuels, such as coal and wood;

(*b*) Artificial fuels, such as coke and charcoal.

Raw fuels. — Coal is often classified as follows:

Coal..... { Lignite. / Bituminous coal. / Anthracite coal.

Plant tissue is really converted into coal by gradual change; hence, each division of the classification covers

a wide range and blends into the others. Description of coals is unnecessary here.

The following table of percentage compositions shows the chemical changes which occur while plant tissue or woody fiber is changed to anthracite coal.

Fuel	Carbon	H and O in proportion to form water	H available for combustion
Wood	48.5	50.9	0.6
Peat	59.4	39.0	1.6
Lignite	65.0	33.0	2.0
Bituminous coal	78.0	19.0	2.8
Anthracite coal	94.0	4.0	2.4

During this change, the percentage of available combustible increases, and the percentage of water to absorb heat decreases; hence, the temperature of combustion increases.

Wood. — According to Professor Thorpe,* woody tissue, when freed from soluble and other foreign matter, has a percentage composition as follows: carbon, 48.5; hydrogen, 6.2; oxygen, 45.3. Since eight parts by weight of oxygen unite in combustion with one part of hydrogen, it follows that if the percentage of hydrogen present were $45.3 \div 8 = 5.6+$, the oxygen and hydrogen would be present in just the right proportion to form water, and no hydrogen would be available for the evolution of heat. The amount of hydrogen really present is 6.2 per cent; and only the difference, $6.2 - 5.6 = 0.6$ per cent of hydrogen is available. This is practically negligible. Only 48 per cent of pure woody tissue, therefore, is available for fuel. The temperature of combus-

* "Coal: Its History and Uses," pp. 164–165. Edited by Professor Thorpe. Published by Macmillan & Co.

tion is low for this reason, and also because the water resulting from the breaking up of the woody tissue, and that present as moisture, must be vaporized with absorption of heat unaccompanied by rise in temperature. Therefore wood cannot be used directly as a fuel for the production of very high temperatures.

Artificial fuels. Coke. — Bituminous coal, as shown in the foregoing table, contains carbon, hydrogen and oxygen. There is also a small amount of nitrogen present.

When this coal is highly heated in a closed retort, destructive distillation takes place. The products of this process may vary with the time occupied, the temperature, the quality of the coal and other conditions, but in general are as follows:

(*a*) Combinations of hydrogen and carbon in a very wide range of proportions, resulting in solid, liquid and gaseous hydrocarbons.

(*b*) Combination of hydrogen and nitrogen into ammonia.

(*c*) Combinations of hydrogen, nitrogen and carbon into aniline and many other compounds.

(*d*) Combinations of carbon, hydrogen and oxygen into phenol and other compounds.

(*e*) Combinations of carbon and oxygen into carbon monoxide and carbon dioxide.

(*f*) Pure hydrogen.

(*g*) A nearly pure residue of carbon which is called coke.

When sulphur is present, sulphur dioxide and other compounds of sulphur and the other elements present are produced.

Charcoal. — Wood may also be subjected to destructive distillation, the process being essentially the same as that just described. The carbon residue is called charcoal.

The object of the processes for the production of coke and charcoal is to produce a concentrated fuel by removing all substances except the available fuel element, carbon. Obviously, this increases the temperature produced by combustion.

Gaseous hydrocarbons, carbon monoxide and hydrogen are gas fuels which pass off, and hence, unless these are utilized, the process sacrifices a portion of the fuel in order to increase the temperature of combustion.

Pulverized coal. — For certain service pulverized coal is used as fuel with great advantage. Bituminous coal is dried and ground so that about 90 per cent will pass through a screen of 100 meshes to the inch; this coal powder is blown into a furnace in a cloud where it burns while in suspension. The surface of contact of the coal with the oxygen of the air is vastly increased by pulverizing and it is unnecessary to supply excess of air as in burning coal in lumps; in fact, the air supply may be kept almost at the theroetical requirement in burning pulverized coal, with the result that the temperature produced approximates the temperature limit set by dissociation of carbon dioxide; because of this, it has been difficult to provide refractory lining that will withstand the temperature of combustion of powdered coal. This fuel requires a very large combustion chamber as the coal powder must be burned while in suspension and the carbon monoxide formed burns with a very long flame; for this reason, it has proved successful for use in the long rotary kilns used in the manufacture of cement, and it has failed as a boiler fuel, though it might possibly be used where the boiler type permits large combustion-space. The temperature, also, is too high for boiler service, but this could be controlled by increase in the air supply.

The pulverized coal under certain conditions forms an explosive mixture with the oxygen of the air, and some very disastrous explosions have resulted. The coal now is ground only as it is needed; it is never stored after grinding; and it is protected from the air while in transit to the furnace.

Liquid fuels. — The liquid fuels of greatest importance are petroleum and alcohol.

Crude petroleum consists of a complex combination of hydrocarbons, with great variations according to its source, together with small and varying proportions of oxygen, nitrogen and sulphur. The constituent hydrocarbons of any crude petroleum vary in composition from C_4H_{10} through a long series of proportions to $C_{13}H_{23}$ with steadily reduced proportion of hydrogen, and with increased density and reduced tendency to vaporize. If the temperature of crude petroleum is steadily raised, the hydrocarbons distill off in an order determined by the proportion of hydrogen present; first gasoline of various grades, then kerosene of various grades, and then lubricating oils of various grades, leaving a residue of hydrocarbons that are solid at ordinary temperatures. There may be also a residue of coke, that is, carbon uncombined with hydrogen.

Crude petroleum is used as a fuel in the furnaces of steam boilers and in several types of metallurgical furnaces. Special burners are used and provision is made for, (*a*) preheating the oil to increase fluidity; (*b*) supplying the oil under pressure; (*c*) delivering the oil for combustion in a very fine spray by the use of steam or compressed air. The temperature limit is the same as for carbon and hydrogen in other forms; but the air to support combustion and the oil of the spray can be so intimately mixed that it is unnecessary to supply an

excess of air and hence, the theoretical limit of temperature can be approached more nearly than with solid fuel.

Alcohol is not yet an important industrial fuel, and it is not used at all for metallurgical purposes; but it may in the future become a very important factor in metallurgy and power development.

The supplies of coal, oil and natural gas will eventually be exhausted, since there is continual draft on a store that is never renewed, and then it will be necessary to supply heat energy for human uses from the sun's energy stored by plant growth of the present time. As already stated, wherever plants grow, carbon is taken from the carbon dioxide of the atmosphere and hydrogen is taken from the water of the sap and they are stored together with oxygen as cellulose, starch or sugar.

Cellulose, the chief constituent of plant fiber, and starch, the chief constituent of grains, potatoes, etc., are isomeric; that is, they contain the same elements in the same proportion, $C_6H_{10}O_5$, but, probably because of some different arrangement of atoms, they are very different substances. Sugar, chemically $C_{12}H_{22}O_{11}$, is found in sugar cane, sugar beets and other products of plant growth. Sugar or starch mixed with water and fermented with yeast yields a weak solution of alcohol which may be condensed by distillation, yielding ethyl alcohol, C_2H_5OH. In starch, $C_6H_{10}O_5$, hydrogen and oxygen are present in proportions to form water and hence only the carbon is available for fuel, while the water, since it must be heated, vaporized and superheated, would absorb a part of the heat of combustion, making it unavailable and thus reducing the temperature of combustion. This is also true of sugar and hence they are not good fuels. But the alcohol produced, C_2H_5OH, has four atoms of hydrogen available for every two atoms of carbon and only one corresponding

molecule of water to absorb heat. Hence, the process that has changed starch or sugar into alcohol has greatly increased the fuel value.

When cellulose, $C_6H_{10}O_5$, is subjected to dry distillation at high temperatures it yields liquid products from which methyl alcohol, or wood alcohol, CH_3OH, may be separated. This change is also accompanied by an increase in fuel value.

If lack of other fuel and reduced price of alcohol made it desirable, alcohol could be burned effectively by the method used for burning crude petroleum, as a source of heat for metallurgical furnaces or for steam boilers. Alcohol could also replace the more volatile petroleum products in internal combustion engines. This would utilize energy coming from the sun year by year in the present, and so the draft would be on a store that nature continually renews. Hence, it offers a possible solution of the fuel problem of the future.

Gas fuel has several advantages over solid fuel for many metallurgical processes.

1. Inferior solid fuel may be used for the generation of the gas fuel.

2. The furnace for the production of the gas may be at a distance from the furnace where the gas is used, the transfer being made through pipes with resulting saving of valuable space.

3. Heat may be more easily applied uniformly over a given surface, or concentrated locally, with gas fuel than with solid fuel.

4. The air which supports combustion can be much more completely mixed with the fuel, and therefore, the excess of air over that necessary for complete combustion is reduced to a minimum, with a resulting increase in temperature.

5. If the mixture of air and gas is properly regulated, there will be a complete absence of smoke and soot, and the latter will not be mixed with the material treated.

Gas fuel may be either natural or artificial. Natural gas, like coal and petroleum, is a product of nature's processes acting through long periods of time upon products of plant growth. Natural reservoirs of this gas are tapped by drilling, usually in petroleum regions, and are piped to places where the gas is used. Natural gas consists chiefly of marsh gas, CH_4, with small amounts of other hydrocarbons, hydrogen and carbon monoxide. All of these constituents are combustible and hence, the heat value is high; from 800 to 970 B.t.u. per cubic foot of gas under standard conditions of pressure and temperature.*

Natural gas is available only in a few limited localities; and, since it is a stored product of nature's very slow processes, the reservoirs are eventually exhausted. While it lasts it is a very valuable fuel.

There are three processes for the production of artificial gas fuels:

1. *Illuminating-gas process.* — This process consists of the destructive distillation of coal containing a large percentage of volatile matter. It is similar to the process for production of coke, with the difference that gas is now the product and coke the by-product. The composition of the gas varies with the fuel and with the conditions of operation, but the variation is not usually very great from the following analysis:

Hydrogen, H.....	49 per cent by volume.
Marsh gas, CH_4.....	34 per cent by volume.
Carbon monoxide, CO...	8 per cent by volume.
Ethylene, C_2H_4.....	4 per cent by volume.
Benzene, C_6H_6.....	1 per cent by volume.

* See "Gas Power" by Hirshfeld and Ulbricht, page 15.

The gas also contains small amounts of incombustible nitrogen, carbon dioxide and water vapor.

The flame from this gas is luminous because of the presence of the hydrocarbons, C_2H_4 and C_6H_6. When these burn with restricted oxygen supply, carbon is separated as a finely divided solid which becomes incandescent and luminous at the flame temperature, and which burns to CO_2 on reaching the flame limit. When the oxygen supply is adequate, as in the Bunsen burner, combustion is complete, no solid carbon appears and the flame is not luminous. The non-luminous flame may, of course, be used for light with mantle burners.

2. *Water-gas process.* — In this process steam is passed through a bed of incandescent carbon. The reactions are as follows:

$$C_2 + 4\,H_2O = 2\,CO_2 + 4\,H_2.$$
$$2\,CO_2 + C_2 = 4\,CO.$$
$$CO + H_2O = CO_2 + H_2.$$

These reactions probably go on simultaneously, and when the process is properly regulated, the composition of the resulting gas is usually within the following limits:

Carbon dioxide, CO_2..... 2 to 15 per cent by volume.
Carbon monoxide, CO... 20 to 40 per cent by volume.
Hydrogen, H..... 50 to 65 per cent by volume.
Marsh gas, CH_4..... 4 to 8 per cent by volume.

There is also present in some cases a small amount of ethylene, C_2H_4; but this is not usually enough to make the flame luminous and hence, if the gas is to be used for illumination, it is passed through a second furnace where it takes up the vaporized hydrocarbons, C_2H_4 and C_6H_6. The breaking up of the steam into its constituent hydrogen and oxygen absorbs heat, and this heat is just equal to that given out when the hydrogen of the gas is burned

again. Hence, there is no gain in heat from the hydrogen that comes from the steam; in fact, there is a loss per pound of steam corresponding to the difference in heat carried by a pound of steam as it comes to the water-gas furnace, and the corresponding pound of steam (superheated) as it is produced in the furnace where the gas is burned. Hence, water gas in burning gives a little less heat than would result from direct burning of the coal used in the water-gas furnace; but the process produces a fuel of high combustion temperature having the advantages of the gaseous form, see page 19.

3. *Producer-gas process.* — This process, the most important to the metallurgist, consists of burning coal with incomplete oxygen supply. There are many forms of gas-producers with great variation in details; the principles of operation, however, can be explained by reference to the form shown in Fig. 1. It consists of a chamber, *A*, lined with fire-brick, and having a suitable grate at the bottom. Coal is introduced through a hopper, *B*, so arranged that communication with the air need not be made when the solid fuel is put in. Air is admitted through the grate, and at *D* there is a steam-blower used to force combustion and to introduce steam. The chamber is connected with the gas-flue by the passage *C*. The most rapid combustion occurs near the grate. Air passes through the grate and its oxygen combines with the incandescent carbon, forming carbon dioxide, CO_2; this in passing up comes in contact with more incandescent carbon where the air supply is limited and taking up more carbon becomes carbon monoxide which passes up into the chamber. In the upper part of the coal where the heat is less intense, the volatile constituents distill off; in fact, the action is the same as in illuminating-gas retorts with the production of hydrogen, hydro-

carbons, carbon monoxide, etc. This leaves coke which descends slowly becoming incandescent and uniting with oxygen and carbon dioxide to form carbon monoxide. Also, steam from the blower passes through the grates with just the same result as in the water-gas process producing

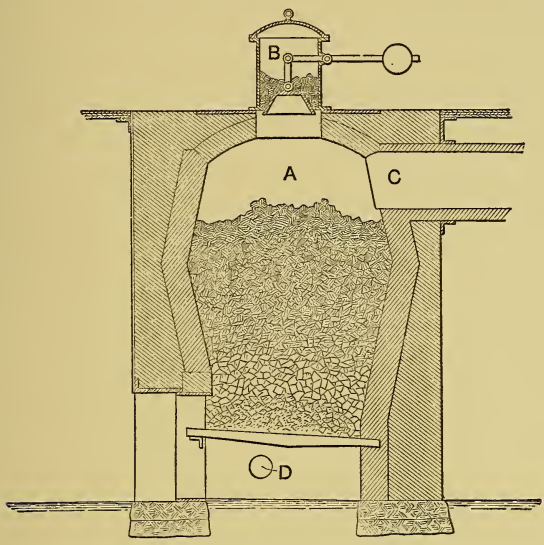


FIG. 1.

hydrogen and carbon monoxide. Since this steam is decomposed into its constituents with absorption of heat, it follows that when the hydrogen burns again it can only restore a part of the heat it has received, and hence the introduction of steam does not add to the heat evolved in the furnace; in fact, it decreases it. But though it is not a source of heat, it gives a convenient auxiliary means of temperature control and also tends to prevent clinkering.

An average of the resulting gases from this process is as follows:

Combustible.....	CO...	24.2 per cent by volume.
	H.....	8.2 per cent by volume.
	CH_4....	2.2 per cent by volume.
Incombustible.....	CO_2....	4.2 per cent by volume.
	N.....	61.2 per cent by volume.

Therefore, 34.6 per cent of this gas is combustible, while 65.4 per cent is incombustible, and hence its combustion temperature must be low. It would seem, therefore, that "producer gas" could not be used for high temperatures. It becomes available for this purpose, however, through the **regenerative furnace,** originally invented by Messrs. Frederick and C. W. Siemens. The gas, instead of being admitted to the furnace directly, passes through a chamber, *B* (Fig. 2), filled with "chequer

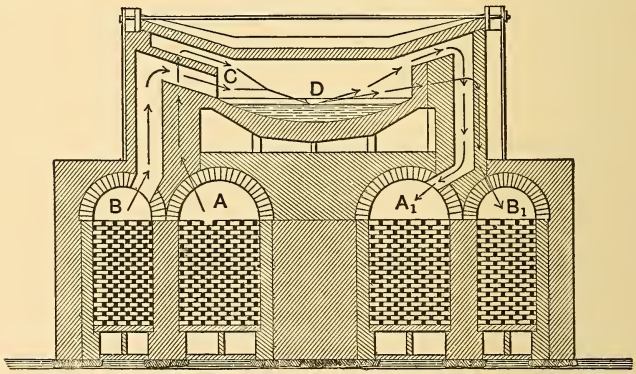


Fig. 2.

work," i.e., full of small intricate passages, surrounded by refractory material suitable for storage of heat. The air also passes through a similar chamber, *A*, and meets the gas at *C*, the entrance to the hearth *D*, where the metal is

treated. The air is admitted above the gas, so that, because of its greater specific gravity, it shall mix more completely with the gas. Combustion occurs at C, and the products of the combustion, heated to a temperature corresponding to the combustion temperature of the fuel, pass over the hearth where they fulfill their function in the treatment of the charge with loss of heat and reduction of temperature, and then pass on, still at very high temperatures, through the chambers A_1 and B_1 to the stack. In passing they heat up these chambers to their own temperature, if the process is sufficiently long continued. Then the connections are changed so that the gas comes in through B_1, and the air supply through A_1, and A and B are connected with the stack. The gas and air passing through the heated chambers have their temperature raised before combustion takes place; then the temperature is still further raised by the combustion, so that the products of combustion now pass to the stack after use in the hearth through A and B until the temperature of these chambers is raised to the higher temperature. Then the connections are again reversed and the entering gas and air are heated to this higher temperature before combustion, and so on. It would seem that an indefinitely high temperature could be produced by this method, but it cannot because a limit, about 3500° F., is set by dissociation of CO_2 into carbon and oxygen at high temperatures with absorption of heat. See page 10.

CHAPTER II

ELECTRIC FURNACES

Electric furnaces are considered here because of the bearing their use has on the temperatures attainable for industrial purposes. Other types of furnaces will be explained and illustrated in connection with their use for metallurgical purposes.

Electric furnaces are usually classified as; arc, resistance and induction furnaces.

Arc furnace. — If carbon electrodes, which have been brought into contact to complete an electric circuit in which a suitable current is maintained, are separated slightly, the carbon of the separated surfaces and the intervening air are heated by the passage of the electricity across the gap. As a result of this heating, the opposing surfaces of the electrodes first grow red and then white and some of the surface carbon is vaporized; the resulting carbon vapor fills the gap, the electricity flows through the vapor, and the gap may then be increased, because the resistance of the carbon vapor is less than the resistance of the air. The electricity thus flowing raises the temperature of the ends of the electrodes and the intervening carbon vapor to incandescence and electrical energy is transformed into heat and light. The light may be used for illumination, as in the arc lamp, or the heat may be used as in the arc-type electric furnace. A limit is set to the temperature that can be produced in this furnace; this limit depends on the supply and disposal of heat. The heat supplied by transformation of electrical energy in the arc is (*a*) radiated to the furnace,

or, (*b*) applied to the vaporization of carbon. (*a*) raises the temperature of the contents of the furnace, but (*b*) disappears as sensible heat and, therefore, does not affect temperature. As the temperature rises the amount of carbon vaporized increases and, therefore, the amount of heat abstracted from the energy supply for this purpose increases and the heat left over to raise temperature grows less. A temperature would finally be reached at which an increase in heat evolved (by the increase in electrical energy in the circuit) would be met by an equal disappearance of heat to maintain increased vaporization of carbon, and with these conditions the temperature would reach a maximum. With an electric arc between carbon electrodes, the temperature probably may reach about 6000° F. and hence the electric furnace furnishes a much higher temperature than a furnace for the combustion of carbonaceous fuel. The vaporization of the substances treated in the furnace might also affect the maximum temperature.

Resistance type. — In this type of electric furnace electrodes have their terminal surfaces separated by a considerable distance and the space between them is filled by some substance, "the resistor," that offers suitable resistance to the passage of the electricity. When the electricity flows its energy is changed into heat and light in the resistor, and the heat is passed on to a substance that needs to be heated for some useful purpose. The substance treated may itself form the resistor, wholly or in part. The temperature attainable in this furnace is the temperature at which there is equality between any increase in the heat supply due to increased flow of electricity in the circuit, and the corresponding increase in heat absorption by vaporization of the resistor or the substance treated.

Induction type. — The induction coil consists of two windings of insulated wire about a suitable soft iron core. When alternating-current electricity flows in one coil, called the primary, an alternating-current is induced in the closed secondary coil. The voltages of the primary and induced currents are nearly directly proportional to the number of turns of wire in the respective coils. Hence, if the primary has a large number of turns and the secondary a small number of turns, a high voltage current in the primary would induce a low voltage current in the secondary. This is, of course, the principle of the alternating-current transformer. Now, if the material to be treated in the furnace can replace the secondary coil a current will be induced in it by the current in the primary coil, and if this current is suitable the required heating effect will be produced. In this type, if the secondary coil is not closed a current in the primary would induce an electromotive force in the secondary, but electricity would not flow. In some cases, the material treated is a solid which is liquefied by heat from the current. In the induction-type furnace, the secondary is closed by this liquid and the closing cannot be effected until the solid is melted and the solid cannot be melted until the secondary is closed. Hence, in starting the furnace, it is necessary to introduce some other material until working conditions are established. This type is, therefore, better fitted for continuous than for interrupted service. The temperature is limited in this furnace exactly as in the others.

Combination of types. — In the arc-type furnace the electrodes often project vertically downward into the furnace with suitable arcing distance between their terminal surfaces and the material treated; two arcs are thus formed and the electricity also passes through the

material treated, which thus acts as a resistor. Hence, this type is really a combination of arc and resistance furnaces. The arc furnace is virtually a resistance furnace in which the vapor between the electrodes is the resistor. In the induction furnace heat is produced by resistance to the flow of electricity in material treated and hence, this type really uses a combination of the **induction** and **resistance** principles.

CHAPTER III

REFRACTORY MATERIALS

Crucibles and the linings of furnaces, ladles and other apparatus for metallurgical purposes must be made of materials having suitable resistance to fusion, to change of form at high temperature and to wasting by chemical or erosive action; also these materials must be so constituted as not to interfere with desired chemical changes, or to cause undesirable chemical changes, in the materials treated by the process.

Acid, neutral or basic linings for furnaces. — Temperatures of incipient fusion of pure refractories are approximately as follows:

Silica, SiO_2 (acid)	3200° F.
Aluminum silicate, $Al_2Si_2O_7$ (neutral)	3300° F.
Chromic oxide, Cr_2O_3 (neutral)	infusible*
Carbon, coke or graphite (neutral)	infusible
Alumina, Al_2O_3 (basic)	3600° F.
Lime, CaO (basic)	4500° F.
Magnesia, MgO (basic)	4500° F.

This table shows silica to be the least satisfactory material for use as a refractory, considering only the temperature of fusion. But, because of other qualities, it is used very extensively where the temperature to be sustained is safely below fusion point.

Lime, CaO, in contact with aluminum silicate at high temperatures yields calcium silicate and calcic aluminate,

* This means infusible at the maximum temperatures now used in industrial processes.

and the mixture is fusible at a relatively low temperature, probably about 2000° F. If magnesia is substituted for lime there is a similar reduction of fusion temperature. Hence, lime or magnesia would act as a flux upon aluminum silicate; and, conversely, aluminum silicate would act as a flux upon lime or magnesia. Hence, wherever alumina, silica and lime are in contact, or wherever alumina, silica and magnesia are in contact, if the temperature is above 2000° F. fluxing will take place; that is, the material will melt. In certain cases this melting is desirable, as, for instance, when refractory alumina and silica are removed from the blast-furnace as a fluid slag by the fluxing agency of lime that is introduced for this purpose (see page 42). But furnace linings must not be fluxed away, and hence the coming together of alumina, silica and lime, or of alumina, silica and magnesia should be prevented where temperatures exceed 2000° F., if any one of the substances is an essential part of the furnace lining. Ferrous oxide, FeO, also acts as a flux upon aluminum silicate.

If a metallurgical process that produces a slag containing lime or magnesia or ferrous oxide is carried on in a furnace lined with material containing excess of silica, that is, with an acid lining, the lining will be fluxed away. Also, with a basic lining and an acid slag, the lining will be fluxed away. Hence, a process producing an acid slag should be carried on in a furnace having an acid lining, and a process producing a basic slag should be carried on in a furnace having a basic lining.

A neutral lining would be best, because it would resist the fluxing action of either an acid or a basic slag; but with the neutral materials at present available, it is difficult to prevent destruction of the linings by other causes.

Kaolin is a fine white clay used as an ingredient of porcelain and other white ware. It consists of a mixture of hydrated aluminum silicate with other substances like hydrous aluminum oxides, feldspar, quartz and mica. It has the quality of becoming plastic when mixed with water, and it thus can be molded into required forms which may be dried at low or moderate temperatures and calcined at higher temperatures with the removal of the water of hydration and with partial fusion. There results a hard, strong, refractory material.

Fire-clay is a clay that is capable of withstanding high temperatures, say a minimum of 3000° F. Fire-clay in addition to hydrated aluminum silicate usually contains varying amounts of lime, magnesia and iron oxide; these, through their fluxing action, increase the fusibility of the calcined material; and hence, the higher the temperature to be sustained the greater the need that these substances should be reduced to a minimum. Fire-clays vary greatly in composition and in physical properties, and hence must be chosen with great care according to the service required; whether it is resistance to fluxing or abrasion, or to the action of gases, or capacity for enduring temperature changes safely. During the calcining of fire-clay considerable shrinkage occurs, which may be accompanied by distortion and cracking. This shrinkage may be reduced by mixing coke dust, graphite or silica sand, or more commonly ground fire-brick or flint clay with the plastic clay. The fitness of clays for use in refractories for given service depends not only upon the chemical composition, but also upon the physical condition and manner of burning. Thus density, porosity and condition resulting from variation of temperature and duration of the burning affect refractoriness.

Silica, when pure, cannot be made into fire-brick or used in mass for furnace linings, because a binding material is necessary. Silica rock, however, often contains enough clay to serve for binding; and often a mixture of ground quartzite or silica sand with fire-clay is used.

Silica bricks are also made by mixing fine silica with a very small proportion of lime and adding water until the mass is somewhat coherent, when it is molded under high pressure, dried and fired. During the firing the lime combines with a small part of the silica and with such small amounts of aluminum as may be present to form a fusible slag that acts as a binder for the silica.

A natural or artificial mixture of a large proportion of siliceous material — usually not less than 90 per cent — with clay or lime or both is usually called **gainster.**

Chromite, $FeCr_2O_4$, a double oxide of iron and chromium, is neutral and very infusible. It occurs in nature as "chrome ore," which contains also alumina, magnesia, lime and silica. Proportions vary, but are often about as follows:

	Per cent
Chromic oxide	50
Ferrous oxide	35
Alumina	3
Magnesia	4
Lime	5
Silica	2

This being neutral would be almost an ideal material for furnace bottoms if it were not for the fact that, after it is molded into place, it is almost impossible to produce a temperature high enough to cause it to set thoroughly, and this leaves it liable to destruction by mechanical erosion. The fusibility of the material varies with the amount and proportion of substances other than chromic

oxide present, and when properly selected, it is a very valuable material for daubing and patching furnace linings.

Carbon in the form of coke or graphite is used as a refractory material either in bricks or crucibles. But though carbon is neutral and infusible, it is such a strong reducing agent, that is, it has such a strong tendency to unite chemically with oxygen, that in the presence of oxygen or oxides of other substances carbon monoxide or carbon dioxide is formed and passes off as gas, thus eventually destroying the crucible or the furnace lining. Carbon, therefore, can only be used as a refractory where oxygen is excluded.

In making carbon refractory forms, tar is sometimes used as a binding material for the coke dust or ground graphite. The mixture is made, formed and dried and then fired with exclusion of oxygen. The tar is coked and the product is practically pure carbon.

Clay is also used as binding material for finely divided carbon. A mixture is made of coke or graphite, clay and water; the mixture is formed, dried and fired. Crucibles made by these methods are used for melting steel in the crucible process.

Bauxite is a mixture of a large proportion of hydrated alumina $Al_2O_3 \cdot 2H_2O$, with clay, silica, iron oxide and titanic oxide; another hydrated aluminum oxide, $Al_2O_3 \cdot 3\ H_2O$, is also often present. Bauxite is used for making basic refractory bricks for furnace linings. To be suitable for this purpose it should contain, after calcining, about 90 per cent of alumina. There is a large amount of combined water in the raw bauxite, a probable maximum being 30 per cent, and the removal of this water during calcining causes great shrinkage and molds must, therefore, be made larger than the required size of the finished bricks. These

bricks are expensive and it is difficult to attain a temperature in firing them high enough to produce a bond that insures requisite strength. Except for these two objections, bauxite bricks provide a very satisfactory basic refractory.

Lime, CaO, is practically infusible, but when pure is not satisfactory as a refractory because of difficulty in getting it to bind, and also, because it slakes rapidly on exposure to the air at ordinary temperatures, forming calcium hydroxide, CaH_2O_2, which crumbles and wastes on reheating. Lime refractories, therefore, cannot be made up and held in stock.

Magnesia, MgO, obtained by calcining magnesium carbonate, $MgCO_3$, is probably the best material for basic furnace linings. Commercially this refractory is obtained from "magnesite," a mineral found in Styria and Greece. The calcined magnesite for "magnesite bricks" contains from 80 to 90 per cent of magnesia; ferric oxide, alumina, lime and silica are present in varying proportions. The plasticity of calcined magnesite depends on the temperature of calcining; if this temperature is about 1500° F. the product has a specific gravity of about 3, while higher calcining temperatures give a specific gravity of about 3.7. The former is plastic enough to mold under pressure, while the latter lacks plasticity. Magnesite bricks may be made of a mixture of from four to six parts of the heavier with one part of the lighter calcined magnesite with from ten to fifteen per cent of water. This mixture is then pressed into molds.

The only objection to magnesia for basic refractories is that it is expensive, because magnesite is found only in few localities far away from metallurgical centers. For this reason "dolomite" or magnesian limestone is often used. This cheaper mineral, after calcining, contains from

50 to 60 per cent of lime, 30 to 40 per cent of magnesia and small amounts of silica, alumina and ferric oxide. Calcined dolomite is ground fine and, either with or without admixture of clay, is made plastic with water, formed and fired. Another method uses tar as a binding material for crushed, calcined dolomite. Plastic dolomite is extensively used for daubing and patching.

CHAPTER IV

OUTLINE OF THE METALLURGY OF IRON AND STEEL

Iron occurs in nature combined with many other substances. The world's supply of iron, however, is obtained almost exclusively from the oxides Fe_2O_3 and Fe_3O_4. Carbonate ores, $FeCO_3$, are reduced before smelting by roasting to FeO; this FeO takes up more oxygen from the atmosphere, becoming Fe_2O_3. The formation of these iron oxides by the processes of nature was accompanied by evolution of heat energy. This energy per unit weight of oxide was definite in amount and independent of the method or time of formation. To separate the oxide again into its constituents an exactly equivalent amount of energy must be supplied. In brief, the separation is accomplished as follows: Heat energy is supplied to the iron oxide whereby its temperature is raised. The bond which holds the iron and oxygen together, whatever its character, is weakened. But this alone is insufficient in this case to cause separation. Therefore, the heating is caused to occur in the presence of carbon (solid) or carbon monoxide (gas). Either of these substances has greater affinity for oxygen at high temperature than the iron; hence, with the help of the heat, is able to pull away the oxygen from the iron oxide, forming CO_2, which, being gaseous, passes off, leaving the iron. The heat energy that is effective to weaken the bond plus the energy expended by the carbon or carbon monoxide in pulling away the oxygen from the iron

is exactly equal to the heat energy that was evolved by the original combination of the oxygen and iron into iron oxide.* The real process is much more complex because of circumstances now to be considered.

Sources of iron. — Full consideration of the ores of iron is beyond the scope of this work.†

Iron ores may be classified as follows:

1. Magnetic oxide, or magnetite, Fe_3O_4.
2. Ferric oxide, or red hematite, Fe_2O_3.
3. Hydrated ferric oxide, or brown hematite, limonite, bog ores, etc.
4. Ferrous carbonate or spathic ore, $FeCO_3$.

These ores always carry other substances, and the proportions vary between wide limits. Sulphur and arsenic are often present, and these, with carbon dioxide and water, may be removed as vapor or gas at comparatively low temperatures by the process of calcining or roasting.

For **calcining or roasting** the ore is piled in heaps out of doors, or charged into kilns, with fuel in proper amount mixed with it. The fuel is ignited, and the mass slowly heated. Water is driven off as steam. If the ore is carbonate, $FeCO_3$, the CO_2 is driven off, and the resulting FeO is changed to Fe_2O_3 by combination with oxygen of the air. If any iron pyrites, FeS_2, is present the sulphur is oxidized, passing off as SO_2, while the iron is also oxidized, remaining as Fe_2O_3. Arsenic is oxidized and vaporized if present. By the process of roasting, the structure of the ore is made more open, and hence better fitted for smelting.

* By the law of conservation of energy.

† "Ore Deposits of the United States," J. F. Kemp; Scientific Publishing Company. "Iron (the Metallurgy of)," T. Turner; J. B. Lippincott Company.

When roasting is carried on in the kilns it is often a continuous process. The kiln is like a foundry cupola, much enlarged in diameter. The ore and fuel are charged in at the top, and the roasted ore is withdrawn from openings at the bottom.

The process is now usually omitted for oxide ores, the roasting being accomplished in the top of the blast-furnace.

The **early methods** for the production of iron were direct methods, i.e., the product was wrought iron, which had not passed through the intermediate state of cast iron.

Chemically these methods were as follows: rich ore, Fe_2O_3 or Fe_3O_4, was charged with charcoal into a rectangular hearth, and air-blast was supplied. The coal was ignited and the oxygen of the air combined with the carbon of the fuel to form CO_2, which passing on over more incandescent carbon was reduced to CO, which came in contact with the Fe_2O_3, when the following reactions took place:

$$3\,Fe_2O_3 + CO = 2\,Fe_3O_4 + CO_2.$$
$$2\,Fe_3O_4 + 2\,CO = 6\,FeO + 2\,CO_2.$$
$$6\,FeO + 6\,CO = 3\,Fe_2 + 6\,CO_2.$$

Metallic iron and CO_2 were, therefore, produced. The silica and alumina of the ore united with FeO formed in the process — see reactions above — to form a double alumino-ferrous silicate or slag, which is fusible at a low temperature, and which was partly drawn off, while the iron remained in the hearth a spongy mass filled with molten slag. The mass was then heated to a welding temperature and taken to a hammer or squeezer, where the slag was removed by impact or pressure, and the mass was welded into a bloom.

The details of this process varied in different localities. Rich ore and charcoal for fuel were required, and there was great waste of iron in the slag. It was, therefore, a

very expensive process, and was not available for the production of large quantities of iron.

Nearly all the iron used to-day is reduced from ore in the **blast-furnace**. Fig. 3 shows a vertical section of a blast-furnace. The height varies from 40 to 100 feet, and the diameter at M varies from 12 to 25 feet. The inside form varies with the kind of ore and fuel used, and with the pressure and quantity of air of the blast.

A blowing engine supplies air, at a pressure of from 5 to 15 pounds per square inch, to the large pipe, P, which surrounds the stack. At intervals of the circumference of this pipe smaller pipes convey the air to the tuyeres, T, T, which deliver it into the furnace. The oxygen of the air combines with carbon of the fuel and forms carbon dioxide, which is almost immediately reduced, in the presence of carbon with restricted oxygen supply, to carbon monoxide. There is a constantly ascending current of carbon monoxide and nitrogen through the constantly descending solid materials.

The "bell," B, prevents the escape of gas from the top of the stack, and insures its delivery into the pipe, G. Solid materials to be introduced into the furnace are placed in the annular space above B, and the latter, which is controlled by power, is lowered periodically and the charge drops into the furnace.

The function of the blast-furnace is to change iron ore into pig iron.

Pig iron is iron carrying from 3 to 10 per cent of carbon, silicon, manganese, sulphur and phosphorus, either chemically combined or mechanically mixed.

The blast-furnace, therefore, provides for:

(a) The removal of volatile constituents of the ore.
(b) The reduction of the iron oxide of the ore.
(c) The removal of the solid earthy constituents of the charge.

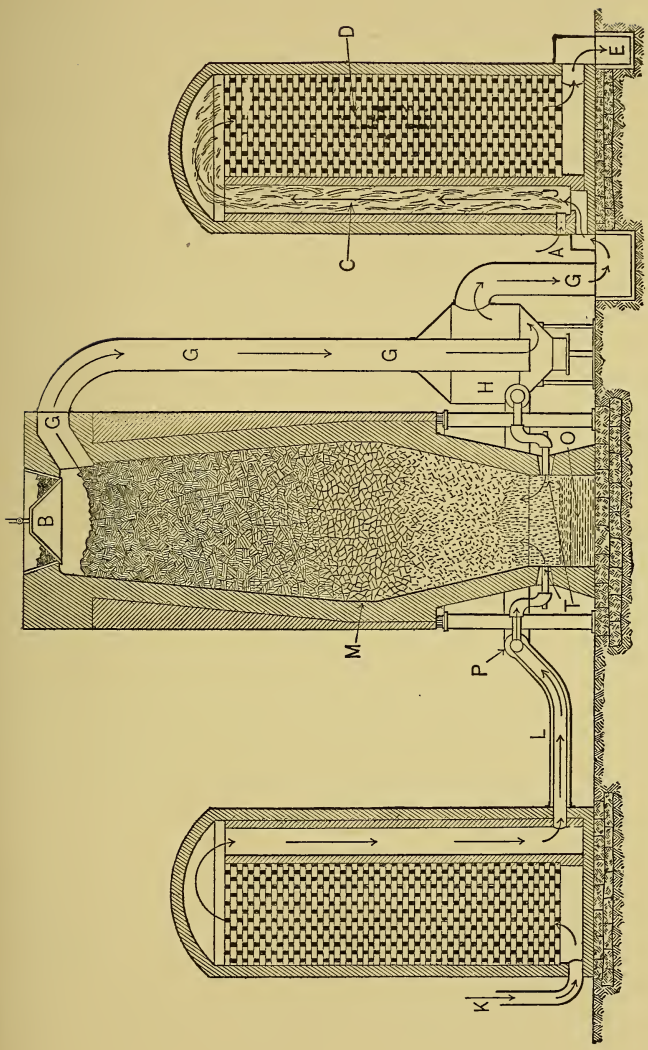


FIG. 3.

It also provides carbon, silicon, manganese, sulphur and phosphorus under proper conditions for absorption by the iron.

In order that the earthy solids of the ore shall combine with the flux into a readily fusible slag, silica, alumina and lime must be present (see page 31). If the ore carries silica and alumina, lime will act as a flux, and it is supplied in the form of limestone. If an ore contains silica only, alumina may be introduced with lime; or, siliceous and aluminous ores may be mixed and fluxed with limestone.

Chemical changes in the blast-furnace. — Ore, coke and limestone are charged into the top of the stack and descend slowly to the crucible, *O*, at the bottom, with steadily increasing temperature. The ore is first roasted, and when the temperature has reached about 450° F., the reduction of iron oxide by carbon monoxide begins slowly and continues at an increasing rate until the temperature reaches about 1100° F., when the reduction is probably nearly complete. The ore has now become a sponge of metallic iron mixed with silica, alumina, etc. But at this latter temperature the flux, which is limestone, $CaCO_3$, begins to give off CO_2, and the lime, CaO, thus produced comes in contact with the silica and alumina of the reduced ore, and they descend together until a temperature is reached at which they combine to form a fusible slag, which melts and leaves the iron sponge.

Introduction of carbon. — In the meantime a deposition of carbon upon the iron sponge has been going on. This may be explained as follows: when carbon monoxide passes over metallic iron at a temperature of about 750° F., the carbon monoxide is decomposed, solid carbon is deposited, and carbon dioxide and ferrous oxide are formed. This is what occurs in the blast-furnace when

the temperature of about 750° F. is reached by the metallic iron sponge. Then, as the temperature rises, ferrous oxide thus formed is reduced again by carbon monoxide, or by solid carbon; the carbon dioxide passes on upward with the gas-current, and the iron sponge remains impregnated with carbon. As this passes down with increasing temperature, iron carbide is formed, which is fusible at a much lower temperature than pure iron; a temperature which is reached below *M* in the blast-furnace. Therefore, the descending iron carbide is raised to its fusion temperature and melts and falls into the crucible *O*.

Introduction of silicon. — At very high temperatures, in the lower part of the furnace, where carbon and silica and metallic iron are in contact, a portion of the silica is reduced, and the resulting silicon is taken up by the iron; the remaining silica goes out with the slag. This change is favored by (*a*) high temperature, (*b*) excess of silica in the charge and (*c*) deficiency of lime in the slag. Usually not more than 5 per cent of the silica of the charge is reduced.

Introduction of manganese. — The manganous oxide of the ore is not reduced by carbon monoxide, but is in part reduced by carbon at high temperatures, and the resulting manganese combines with the iron. The unreduced manganous oxide passes into the slag. Certain ores, like New Jersey franklinite, contain very large proportions of manganous oxide, and the product of their smelting is spiegeleisen, or ferro-manganese, containing from 5 to 25 per cent manganese.

Introduction of sulphur. — Only a small part of the sulphur in the charge, which is chiefly in the coke as iron sulphide, FeS, appears in the pig iron, the rest passing into the slag as calcium sulphide. The amount of sul-

phur that the iron can take up depends upon the capacity of the iron itself for sulphur, and also upon the amounts of silicon and manganese present (see page 128). High furnace temperature tends to reduce the amount of sulphur in the pig iron. Also basic slag, i.e., slag with excess of lime, combines readily with sulphur, thereby reducing the amount absorbed by the iron.

Introduction of phosphorus. — The phosphorus of the charge is usually in the ore in the form of calcium phosphate. This is not changed by carbon monoxide. But when the part of the furnace is reached where the slag is formed, the calcium phosphate is reduced in the presence of solid carbon. The lime goes to the slag; the phosphoric anhydride is broken up with formation of carbon monoxide and iron phosphide. Practically all of the phosphorus of the charge appears in the pig iron.

Descent of coke. — Coke is the fuel almost universally used in "hot-blast" furnaces. As the coke descends it is dried and raised in temperature. It meets carbon dioxide, which may come from the reduction of iron oxide, or from the roasting of carbonate ore, or from the roasting of limestone. The carbon dioxide is reduced to carbon monoxide with absorption of heat. The resulting carbon monoxide may take part again in reduction, or, if it is near the top of the stack, may pass off unchanged with the gas-current. The coke may also supply part of the carbon for formation of carbureted iron, and it also helps in the reduction of silica and phosphoric anhydride. When it reaches the vicinity of the tuyeres it burns to CO and evolves the heat necessary for the operation of the furnace. All of the carbon of the coke appears either in the pig iron or in the gases issuing from the top of the stack.

The combination of iron, carbon, silicon, manganese,

sulphur and phosphorus is fusible at a temperature which is reached a little below *M* in the blast-furnace. Hence, fusion occurs and the melted substance falls into the crucible, *O*, together with the fluid slag. The iron and slag separate because of their difference in specific gravity, the slag floating on the top. When a sufficient amount has accumulated, the slag is tapped out through the "cinder-notch," allowed to cool, and transferred to the "cinder dump." The iron is tapped out through a hole low down in the crucible and allowed to run out through properly formed sand channels, where it cools as pig iron.

Fig. 4 gives Professor Diederich's diagrammatic summary of blast-furnace operation. While this does not pretend to give exhaustively all changes that occur, it does give the changes that are fundamentally important. The figure is self-explanatory.

Obviously, a continuous current of gas flows from the top of the blast-furnace stack. The chief constituents of this are nitrogen, carbon dioxide and carbon monoxide. When the furnace is properly regulated, the carbon monoxide equals about 25 per cent of the issuing gas. It is, therefore, a gas fuel. A portion of this is often burned in the boiler furnaces to make steam to run the blowing engines and other auxiliary machinery. In some modern blast-furnace plants the stack gas is used as a fuel in internal-combustion engines which develop power for the entire plant. The rest of the stack gas is used for heating the blast.

In early blast-furnaces the blast entered the furnace nearly at the temperature of the outside air. Cold blast is still used in furnaces for the smelting of some special grades of iron.

Heating the blast on its way from the blowing engine to the tuyeres results in:

Reactions

$$2\,Fe_2O_3 + 8\,CO = 7\,CO_2 + 4\,Fe + C.$$
$$2\,Fe + 3\,CO = Fe_2O_3 + 3\,CO.$$

$$CaCO_3 = CaO + CO_2.$$

CO_2 rises through the stack.

CaO passes down and, when temperature is high enough, fluxes with the gangue to form the slag.

In the entire limestone decomposition range the following reaction occurs:

$$CO_2 + C = 2\,CO.$$

C comes from the coke and the reaction (called carbon transfer) is not desirable as it carries CO out of the furnace.

PROF. DIEDERICHS' BLAST-FURNACE DIAGRAM

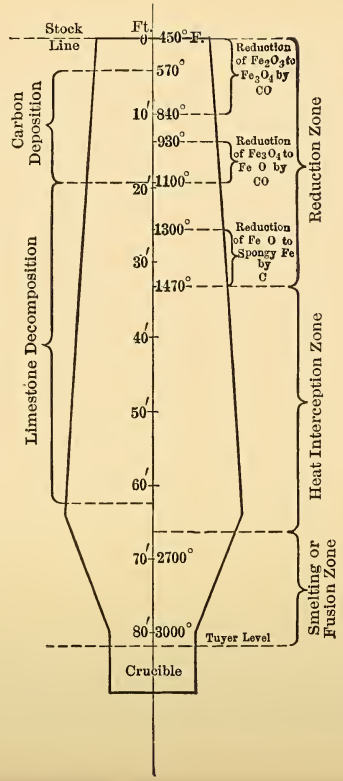


FIG. 4.

Reactions

$$3\,Fe_2O_3 + CO = 2\,Fe_3O_4 + CO_2.$$

$$Fe_3O_4 + CO = 3\,FeO + CO_2.$$

$$FeO + C = Fe + CO.$$

In this zone all parts of the charge are heated as they pass downward. The spongy metallic Fe formed above is gradually impregnated with carbon from the carbon deposition or from contact with fuel, and the formation of the iron-carbon alloy together with the rise in temperature finally causes fusion of the iron near the lower limit of the zone; where also the CaO becomes very active, uniting with the gangue to form the slag.

In this zone fluid iron and slag trickle down over the coke into the crucible. The following reactions may also occur here:

$$SiO_2 + 2\,C = Si + 2\,CO.$$
$$MnO_2 + 2\,C = Mn + 2\,CO.$$
$$P_2O_5 + 5\,C = 2\,P + 5\,CO.$$
$$FeS + CaO + C = CaS + Fe + CO.$$

Higher temperature (see page 11).

Economy of fuel, because the blast is heated by the waste gas fuel from the top of the blast-furnace stack, and less fuel needs to be burned in the furnace to maintain a given temperature.

Increased capacity, because, since less coke is charged, ore and flux may take its place.

Grayer pig iron. — The higher temperature in the hot blast-furnace favors the reduction of silica, and the presence of silicon in the iron causes a large part of the carbon to crystallize out as graphite, i.e., it renders the iron gray.

The first method of heating the blast was to pass it through cast-iron pipes, which were enclosed in a furnace and maintained at the highest temperature that is safe for the material of the pipes. The temperature, however, is only about 900° F. In order that a higher blast temperature may be reached, special hot-blast stoves have been designed. The Cowper type is shown in Fig. 3. It consists of a cylindrical shell of iron plates lined with fire-bricks. *C* is a combustion-chamber, and *D* is a chamber filled with "chequer work." The gas fuel from the top of the stack passes through the pipe *G*, the dust-separator *H*, and into the combustion-chamber at *J*. Here it meets air which enters at *A*, and combustion takes place. The heated products of combustion pass down through *D* and on through *E* to the chimney. This process is continued until the combustion-chamber and the chequer work are raised to the temperature of combustion. In the meantime the air from the blowing engine enters the other stove (which has been previously heated) at *K*, passes up through the chequer-work chamber, and down through the combustion-chamber. The air gains heat from the chequer work and is thereby raised to a temperature somewhere between 1000° and 1500° F.

It then passes through L and P to the tuyeres T, where it enters the furnace. When this stove is cooled so that the blast is insufficiently heated, properly arranged valves are changed, and the gas burns in the stove at the left, while the blast enters through the stove at the right.

Since the action of the blast-furnace is continuous, there must be at least three stoves, so that any one may be put out of service for cleaning or repairs.

There are still some blast-furnaces that use charcoal as fuel, with cold blast. The product is white iron. Because of the lower temperature in the furnace less silica is reduced, and less silicon is absorbed by the iron. Because of the small amount of silicon the carbon combines with the iron, instead of separating as graphite, and the iron fracture is white. This iron is used for chilled car-wheels, malleable cast iron, etc.

Dry blast.* — It has been known for many years that the variation of moisture in the air seriously affects the operation of the blast-furnace. The air-blast enters the furnace and strikes the white hot material of the descending charge including the coke. The heat in this part of the furnace is increased by combination of oxygen of the air with carbon of the coke; but it is decreased by the sensible heat required to raise the temperature of the blast to the furnace temperature. If the air is free from water vapor, only nitrogen and oxygen (in its combination with carbon) absorb heat; but if the air carries water vapor this also has to be heated. Although the percentage by weight of the vapor in the air is small, yet its heat capacity — specific heat — is more than twice as great as that of nitrogen, and hence, high humidity of the air may chill the furnace and interfere with satisfactory

* See *Journal Iron and Steel Institute*, Vol. LXVI, 1904, Part II, page 274.

operation. Of course, with any amount of vapor the temperature in the furnace could be maintained if there were coke enough in the portion of the charge where the blast enters; but the water vapor in the air is subject to sudden and irregular variations, and it is impossible to adjust the quantity of coke at the tuyeres to meet these variations because of the long time required for the descent of the charge. The ideal condition is with air for the blast with a **uniform minimum** of water vapor.

Mr. James Gayley designed a plant for furnishing "dry-air blast," which was constructed and applied to the Isabella furnaces of the Carnegie Steel Company at Etna, Pa., and started August 11, 1904. Mr. Gayley's scheme is as follows: The air on its way to the blowing engine passes through a chamber containing coils of pipe that are kept at a low temperature through the agency of an ammonia-compression refrigerating plant. The moisture in the blast air is deposited on the coils as water or frost; and, after the accumulated frost has reached a certain thickness, the refrigerating medium flowing in the coils is shut off and a hot medium, which melts the frost, is forced through in its stead. The resulting water is drawn off, the refrigerating conditions are restored and frost begins to form again. The frost-melting process is applied to a few coils at a time and does not interfere with continuous running.

The introduction of this dry-air blast makes it possible to increase the burden — the weight of ore per ton of coke — by an amount equal to 20 per cent or more with proportionate decrease in cost of fuel per ton of product. Also, since the air after passing the drying chamber reaches the blowing engines at a reduced temperature and increased density, the weight of air delivered per engine stroke is increased and the engine speed is reduced

with corresponding gain in power cost. In the experimental plant this gain in power in the blowing engines was greater than the power required to drive the refrigerating plant. But the greatest gain from Mr. Gayley's invention results from the power of control that it gives over conditions of operation. It becomes possible as never heretofore to turn out different grades of pig iron at will, and thus to command the most profitable market.

Pig iron from the blast-furnace goes either (*a*) to the foundry to be converted into castings, or (*b*) to the puddling mill to be converted into wrought iron, or (*c*) to the Bessemer mill to be converted into Bessemer steel or (*d*) to the open-hearth furnace to be converted into open-hearth steel.

In the **foundry** pig iron is melted, with very little chemical change, and poured into sand molds, where it solidifies in the required form. This material is called **cast iron.**

The pig iron is melted in a cupola-furnace. See Fig. 5. This consists of a plate-iron shell lined with fire-brick and supported upon standards. Double doors, *A*, opening downward, are closed and held in position by a prop, *P*, and a sand bottom is rammed into place with a slope toward the tapping-hole *T*. The top of the cupola is open.

A fan or blower supplies air-blast at a pressure of from 5 to 10 ounces per square inch. The air enters through the pipe *B* and passes into the furnace by way of the chamber *C* and the openings *E*.

The charge is elevated to a platform, indicated at *F*, and is introduced into the furnace through the charging-door *D*. Kindling and wood are first laid upon the sand bottom. Upon this the "bed" of coke is charged, and then alternate layers of iron and coke until the level of the

charging-door is reached. The fire is lighted and the blast turned on. The coke burns, and the iron melts; and as the top of the charge settles gradually, more iron and coke are "charged on."

The melted iron collects in the bottom and is drawn off periodically at *T* into a receiving ladle, from which it is distributed. Since the hot iron comes in contact with the air-blast there is always silica produced by the oxidation of some of the silicon. Also, a considerable amount of silica sand is introduced into the cupola adhering to the pig iron. If the cupola only runs one or two hours a day, as in small foundries, the silica does not interfere with operation. But for long or continuous running it is necessary to include limestone with the charge for a flux, and to tap off slag at *S*.

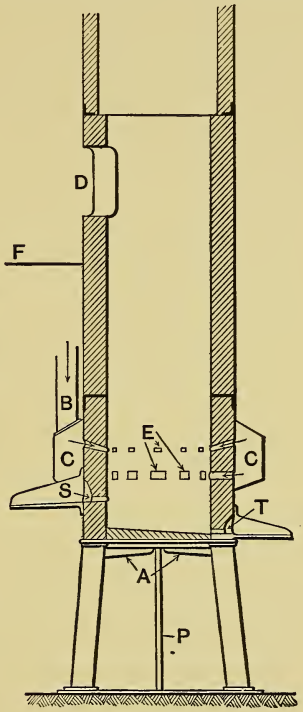


Fig. 5.

After all the iron to be melted has been charged into the cupola, the drawing off of melted iron continues and the charge settles down until the cupola is empty except for slag and a little iron. The blast is then stopped, the prop *P* is knocked out, the doors *A* swing down, and the residue of slag and iron drops out.

Puddling process. — Both pig iron and wrought iron contain silicon, manganese, carbon, sulphur and phos-

phorus; but in pig iron the sum of these is usually from 3 to 10 per cent, while in wrought iron their sum does not usually exceed 1 per cent. The object of puddling is to change pig iron into wrought iron. The process must, therefore, provide means for the removal of a part of these substances. The removal is effected by oxidation and the puddling process is carried on in a reverberatory furnace. This furnace requires description.

See Fig. 6. *A* is a fire-box provided with a grate upon which solid fuel is burned. *H* is a hearth in which the metallurgical operation is carried on. *E* is a passage

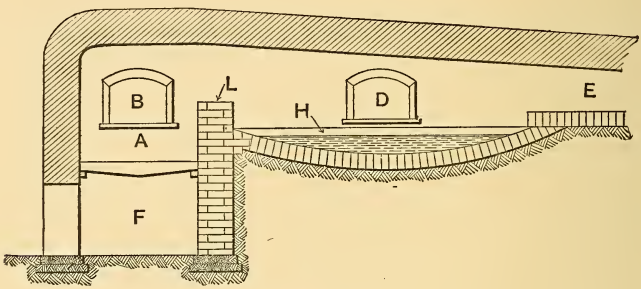


Fig. 6.

connecting with the stack. *F* is the ash-pit, and *B* and *D* are doors for the introduction of fuel and the material to be treated in the hearth. The material in the hearth is heated by the hot gases which pass over it, and also by heat reflected from the highly-heated refractory material of the furnace roof. Solid fuel burns on the grate, and the air-supply through the ash-pit is under control. If air-supply were just sufficient for perfect combustion, the resulting carbon dioxide and nitrogen, at the temperature of combustion, would pass over the hearth and give up part of their heat to the furnace walls, and to the ma-

terial in the hearth, and then go on at lower temperature to the stack. But if air-supply is more restricted, carbon monoxide will result, which will burn in the hearth with air admitted above the fire or through the bridge-wall *L*. In this case the fire-box becomes a gas-producer, and the gas burns in the hearth.

The flame which passes over the hearth of this furnace may be made an **oxidizing,** a **neutral** or a **reducing** flame. Thus, by a free admission of air through the fire or above it, complete combustion of all carbon monoxide is insured, and an excess of oxygen is carried over the hearth with the products of combustion. This results in a tendency to oxidize materials in the hearth. If the admission of air is so regulated as to supply only just enough oxygen to complete the combustion of all carbon monoxide, the flame will be neutral, i.e., it will not tend either to give out or to take up oxygen. If the air-supply is restricted below the fire, carbon monoxide will result from the incomplete combustion; and if no air is admitted above the fire, this carbon monoxide will tend to take up oxygen from the materials in the hearth or to **reduce** them.

In the form of reverberatory furnace used for puddling, the bottom of the hearth is made up of cast-iron plates which are covered to a depth of about three inches with a lining or "fettling" composed of silica and oxide of iron. The fettling is put in as follows: tap-cinder (which may be represented thus: $2\,FeO,\,SiO_2$) is charged in upon the iron plates, spread evenly, and subjected to a temperature high enough to soften it in the presence of oxygen. The FeO takes up oxygen and becomes Fe_2O_3. This will not remain in combination with the silica, and hence, the fusible silicate is converted into infusible ferric oxide and silica. Then scrap iron is charged in and subjected to

an oxidizing flame. It is thereby changed to magnetic oxide, which is raised to a welding heat and spread smoothly over the hearth bottom.

If the hearth were lined with silica, the lining would be fluxed away by the ferrous oxide formed during the puddling process, with considerable loss of iron. Also, it is impossible to remove phosphorus in the presence of free silica.*

There are two puddling processes: **dry puddling** and **wet puddling.** In the first, and less used process, white pig iron is heated in the hearth of the reverberatory furnace and subjected to the action of an oxidizing flame. White iron differs from gray iron in passing through an intermediate pasty condition before melting. During the passage through this condition, the iron is constantly stirred with a "rabble" or iron bar, which is inserted through a hole in the door *D*. The order in which oxidation of substances occurs is silicon, manganese, carbon, iron. A considerable part of the silicon and manganese is oxidized during the melting, and ferrous oxide also is formed. The silica and manganese oxide combine to form silicate of manganese, a fusible slag, and if silica is still left free it combines with ferrous oxide to form silicate of iron, also a fusible slag. When the silicon and manganese are completely oxidized, the oxygen attacks the carbon and iron at the surface of the bath of metal. The resulting carbon dioxide passes off to the stack, and ferrous oxide acts as a carrier of oxygen, i.e., it is mixed with the bath and gives up its oxygen to combine with the carbon of the iron carbide, and the result is that carbon monoxide bubbles up to the surface of the bath and burns there to carbon dioxide, while the iron of the oxide and carbide remains in the hearth. This continues until the

* See page 61.

carbon is almost entirely removed. Then, because of the raising of the fusing-point, the iron begins to solidify and is collected in a "puddle ball," which is really a sponge of iron with its interstices filled with slag. This is raised to a welding temperature, and put through a **squeezer,** where the slag is squeezed out and the iron is welded into a "bloom." This bloom is then put through a "roughing train" of rolls and is thereby converted into "muck bar," which is cut up, piled, reheated, welded under a hammer and rolled into "merchant bar." This piling, heating and rolling is sometimes repeated, with a resulting product of finer fiber and increased strength and ductility.

In wet puddling, the more commonly used process, gray iron is used, and it is allowed to become entirely fluid before it is "rabbled." The oxide of iron in this process, instead of being formed in the furnace, is derived from the fettling or is introduced in the form of "mill scale," * or from slag of previous heats that is rich in ferrous oxide or from some kind of rich ore.

The chief distinction, then, between the two puddling processes is that in dry puddling the oxygen is supplied by the air, while in wet puddling the oxygen comes from the oxide of iron which is introduced with the pig iron.

In order that the phosphorus may be removed it is necessary that there should be an excess of ferrous oxide in the fettling and the slag. Then phosphorus is oxidized to P_2O_5, and this combines with FeO to form ferrous phosphate, $Fe_3P_2O_8$. This is the form in which the phosphorus appears in the slag. If there had been uncombined silica present in the slag the phosphoric anhydride would have been reduced again to iron phosphide and

* The iron oxide that scales off from iron when it is hammered or rolled.

the phosphorus would have appeared in the iron instead of in the slag.

Sulphur is removed in the puddling process, but the manner of its removal is not clearly understood. The sulphur exists in the pig iron as iron sulphide, and it appears in the slag in the same form. A basic slag (i.e., slag with excess of ferrous oxide), and a long period of contact of iron with the slag, are favorable to the removal of sulphur.

A process is sometimes used which is intermediate between the blast-furnace process and the puddling process. It is called **refining.** It removes most of the silicon and manganese, but stops the process of removal before the iron becomes too infusible to be cast. The furnace for this process is a rectangular hearth with tuyeres on two sides bringing air under pressure. Melted iron from the blast-furnace may be run into this furnace and subjected to the oxidizing air-blast, or pig iron may be charged in with coke to melt it. In either case iron oxide may be introduced to hasten the removal of silicon and manganese. The iron, after completion of the treatment, is drawn out into sand molds, where it cools in the form of plates. These plates are broken up and converted into wrought iron in the puddling-furnace. The refinery changes gray pig iron into white pig iron, because it removes the silicon, which causes much of the carbon to change into graphite during cooling.

Processes for making tool-steel from wrought iron. — The difference between wrought iron and tool-steel is chiefly in the amount of carbon contained.

Wrought iron has from 0.1 per cent to 0.3 per cent.

Tool-steel has from 0.5 per cent to 1.5 per cent.

The change from wrought iron to tool-steel is, therefore, to be effected by addition of carbon.

Cementation Process. — Bars of very pure wrought iron, about $\frac{5}{8}$ inch by 5 inches by 12 feet long, are packed in refractory boxes about 3 feet wide by 3 feet deep, with alternate layers of rather finely divided charcoal. These boxes, which are sealed up to exclude the air, are placed in a furnace, where the temperature is gradually raised to a maximum of 2000° F.; this temperature is maintained for several days, and then the furnace is allowed to cool down. Iron in contact with carbon at a high temperature tends to absorb carbon slowly, and it is found that the bars, after treatment as described, are changed to steel. The carbon, however, is not uniformly distributed, the structure is coarse, because of long-continued high temperature, and the material is brittle. This material (called blister-steel) is changed to tool-steel by the crucible process, as follows:

Crucible process. — The blister-steel is broken up into small pieces and charged into refractory crucibles about 2 feet high, with an average diameter of about 10 inches. These crucibles are placed in a furnace, usually of the Siemens' regenerative type, where the melting temperature of steel can be attained, and their contents can be fused. This fluid steel is then cast into an ingot, which is homogeneous chemically, but of coarse, crystalline structure, because of its **heat treatment.** It is then reheated and hammered into standard sizes and forms, and the mechanical working gives it a fine homogeneous structure.

The cementation process is often omitted and wrought iron is charged into the melting crucibles together with cast iron free from sulphur and phosphorus to furnish carbon. Coke or charcoal may be charged also to prevent oxidation at the surface, and to serve as a source of carbon. Some carbon may be absorbed from the cru-

cibles which contain either graphite or finely divided coke. Either ferromanganese or spiegeleisen * is introduced into the crucible, because the manganese reduces any iron oxide that may be present, and removes gas or causes it to go into solution, thus preventing porosity. The carbon of the ferro or spiegel increases the carbon of the steel. The melter regulates these sources of carbon so as to insure close approximation to the required grade of the product.

The Bessemer process. — Bessemer steel is very similar to wrought iron in chemical composition, but usually contains a little more carbon. The structure, however, is different, because of the difference in the method of manufacture. Thus wrought iron is built up from small particles of iron covered with slag. The slag is not entirely removed and the process of rolling draws out the particles into threads that are still surrounded by slag. This gives wrought iron the appearance of a fibrous structure. But Bessemer steel is cast into a solid ingot and then drawn down to the required shape and size. It, therefore, shows the crystalline structure of the iron itself.

The Bessemer process changes pig iron into steel containing from 0.1 per cent to 0.6 per cent of carbon. This change is accomplished in a vessel called a **converter.** See Fig. 7.

The vessel is made up of riveted iron or steel plates, and is lined with "ganister."† The converter is mounted upon trunnions A, A, and can be turned about the axis of the trunnions into any required position. Cold air from a blowing engine, at a pressure of from 20 to 25 pounds per square inch, enters at E, follows the passage shown

* See page 43.

† See page 33.

to *F*, whence it passes into the converter through holes about $\frac{3}{8}$ inch diameter that pierce the conical fire-bricks shown in the converter bottom.

The Bessemer plant includes cupolas for melting the pig iron. The melted iron is conveyed to the converters either through properly-formed channels with refractory linings, or in ladle-cars running upon a track. Sometimes

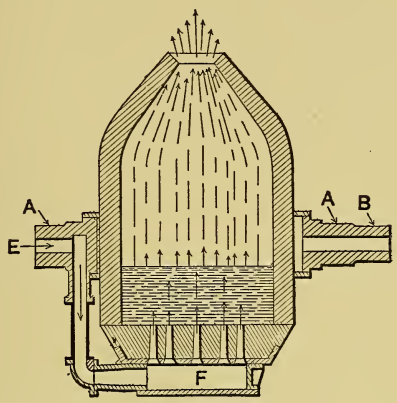


Fig. 7.

these cars transport the fluid iron directly from the blast-furnace to the converter.

The converter is turned on its side, and a charge of iron is run in. It is then turned into a vertical position, a valve opens automatically to turn on the blast, and the air is forced through the bath of iron. The results are as follows:

The oxygen of the air combines with the oxidizable substances of the bath; and, iron being in excess, ferrous oxide is formed throughout the entire "blow." But ferrous oxide is reduced by silicon that is present with

formation of silica. Silica is also formed by direct combination of silicon with oxygen of the air. Manganese also is present and oxide of manganese is formed; this combines with silica to form silicate of manganese, a fusible slag. If the silica is in excess, some fusible silicate of iron is also formed. During this period brilliant sparks of slag are thrown from the mouth of the converter.

When all the silicon and manganese are removed, the carbon begins to be oxidized, directly by the oxygen of the air, and indirectly by the oxygen of the ferrous oxide. Carbon monoxide is formed, which passes off from the bath, and on reaching the mouth of the converter burns to carbon dioxide in a long flame. When the oxidation of the carbon is complete, there is no substance left to reduce the iron oxide formed, reddish fumes appear at the mouth of the converter, and the process is immediately stopped by turning the converter on its side.

The converter now contains nearly pure iron, and, although its fusion temperature is about 2900° F., it remains fluid. The fuel which, by its oxidation or combustion, has raised the temperature of the converter from the melting-point of pig iron to that of wrought iron, is the silicon, manganese and carbon of the pig iron.

When the first experiments were made on the Bessemer process, it was thought that the blow could be stopped at the right point to leave the amount of carbon necessary to make steel; but it was impossible to get a uniform product, and the resulting metal was brittle and worthless.

This was because iron oxide remained in the metal, and because gas was occluded, causing porosity. To overcome these difficulties, the blow is continued until the carbon is completely removed, and a known proportion

of spiegeleisen or ferromanganese * is added to effect the recarburization. The manganese reduces the iron oxide, and, in some not very well understood way, removes the occluded gases or causes them to go into solution. After the addition of the spiegel or ferro, the steel is poured from the converter into a ladle, from which it is cast into ingots, which are rolled into rails, or plates, or into blooms which are to be rolled or forged into required forms.

The basic Bessemer process. — During the blow as described, phosphoric acid and ferrous oxide are formed simultaneously, and these combine to form phosphate of iron, or ferrous phosphate; thus $3\,FeO + P_2O_5 = Fe_3P_2O_8$. But this is reduced again to iron phosphide by **silicon** and **carbon,** and, therefore, little or no phosphorus can be removed until after the complete removal of these substances from the metal in the converter. Ferrous phosphate is also reduced by **silica,** because the silica has greater affinity for ferrous oxide than phosphoric acid has, and so ferrous silicate is formed and phosphoric acid is left, which is probably reduced to iron phosphide by the metallic iron, with formation of ferrous oxide.

The lining of the Bessemer converter described is largely silica, and, therefore, silica is always present, and no phosphorus can be removed in a converter with a ganister or acid lining. It is necessary, therefore, to use for this process pig iron which is very low in phosphorus, since the presence of phosphorus in the product in any considerable amount is very undesirable.

The fact that a large proportion of the iron ore of the world contains phosphorus, which is not removed in the blast-furnace, made it desirable to find a way to eliminate phosphorus in the steel-making process. This led to the

* See page 43.

invention of the basic Bessemer process, in which a lining of lime and magnesia is substituted for ganister in the converter. The only free silica, then, is that which results from the oxidation of the silicon in the pig iron. This combines with lime, which is charged into the converter before the blow, and forms a stable slag, the silica being thereby rendered powerless to reduce the ferrous phosphate.

The lime or magnesia present then replaces the ferrous oxide of the ferrous phosphate, forming calcium or magnesium phosphate, which is probably the form in which the phosphorus chiefly exists in the slag.

In the acid process iron is not usually used which contains less than 2 per cent of silicon, because the combustion of at least that amount of silicon is necessary to produce a sufficiently high temperature in the converter.

In the basic process silicon is an undesirable element, since all the silica produced must be neutralized by lime, in order that the process shall succeed. For this reason iron with 0.5 per cent silicon is best, and 1.5 per cent is the highest allowable limit. This makes it necessary to substitute some other fuel, and, therefore, pig iron high in manganese is used. The phosphorus, usually present from a minimum of 1.5 per cent to 3 per cent, is also a fuel and raises the temperature during the "afterblow." In the basic process little or no phosphorus is removed until after the complete removal of the carbon, and the blow has to be continued after the "dropping" of the carbon flame. The duration of the afterblow is determined from a knowledge of the amount of phosphorus in the pig iron used, or by taking samples at intervals during the afterblow and making physical tests.

The steel after the afterblow of the basic bessemer process must not be recarburized in the converter, be-

cause, in the presence of the spiegeleisen or ferromanganese, the phosphorus compounds of the basic slag tend to be reduced, the phosphorus liberated returning to the iron. Hence, the iron and slag in the converter are separated as completely as possible by (1) pouring off the liquid slag from the iron and then (2) pouring the iron into a ladle, leaving the partly solidified basic slag in the converter. Then the fluid iron in the ladle freed from slag is recarburized in the usual way by the addition of spiegeleisen or ferromanganese. The iron is oxidized to a greater extent in the basic than in the acid blow,* and hence, more manganese is required to deoxidize the iron.

The best pig iron for the basic process contains:

	Per cent
Phosphorus.....about	3
Manganese.....over	2
Silicon.....about	0.5
Sulphur.....less than	0.1

This is white iron, because of high manganese and low silicon, whereas the high silicon iron used in the acid process is gray.

Control of temperature in the Bessemer converter. — Either too high or too low temperature of the steel at pouring results in porosity, and, therefore, this temperature

* Possibly because in the acid process the time for stopping the blow is indicated definitely by the appearance of the red fumes of iron oxide, whereas the time for stopping the blow in the basic process can only be determined by the knowledge of the amount of phosphorus in the charge and knowledge of the rate of removal, checked by tests of the bath for phosphorus. Hence, the tendency to overblow in the basic is greater than in the acid process, with the probability of a greater amount of free oxygen and iron oxide in the blown metal.

must be carefully regulated. If iron too high in silicon is used in the acid process, too high temperature results, and conversely.

In the basic process the difficulty is usually to keep the temperature high enough. If the temperature is too high, it may be reduced by charging in scrap-steel from the mill, which is thus remelted, absorbing surplus heat, and is rendered available for use. The temperature is also sometimes reduced by admitting a small amount of steam into the blast-pipe.

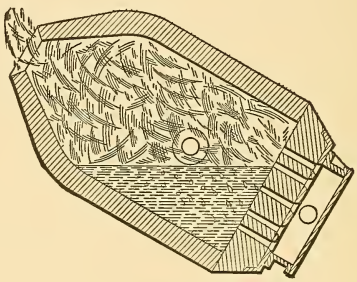


Fig. 8.

If the temperature becomes too low, the converter may be inclined, as shown in Fig. 8, during the burning out of the carbon. When the converter is vertical the carbon monoxide formed burns at the mouth of the converter, and the heat evolved is lost as far as raising the temperature inside of the converter is concerned. In the inclined position, however, a part of the air of the blast passes through the metal bath and forms carbon monoxide, and a part passes through the uncovered tuyere holes and furnishes oxygen to the carbon monoxide, and carbon dioxide is formed; i.e., combustion occurs inside

of the converter, and the heat developed raises the temperature of the metal bath.

Graphical representation of the basic Bessemer process. — Fig. 9 is copied from Wedding's "Basic Bessemer Process," * page 143. The diagram is plotted from the results of experiments and shows the history of a blow in a basic converter. Horizontal distances from *O* represent time, each division corresponding to one minute. Vertical distances from *O* represent percentages of the substances to be removed. Therefore, the curves represent the change in percentage of the substances during the blow.

The silicon is reduced very rapidly from 1.2 per cent at the beginning of the blow, and after six minutes only

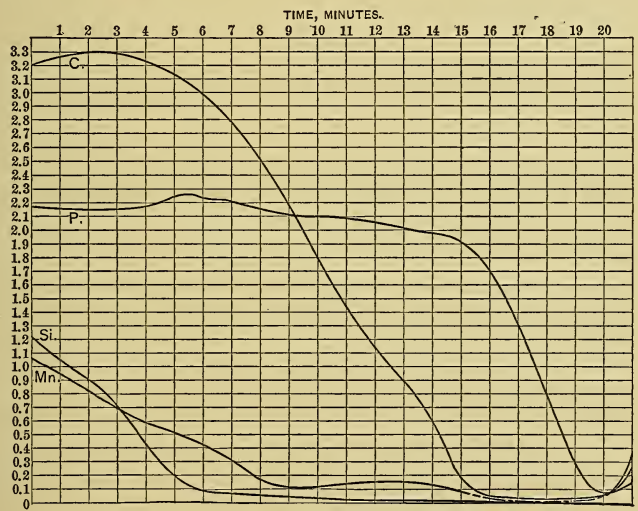


FIG. 9.

* Translated by Phillips and Prochaska; E. & F. N. Spon, publishers, London.

0.1 per cent remains. From this point on the silicon is slowly reduced to zero.

The manganese is reduced less rapidly than the silicon, changing from 1.05 per cent at the beginning to 0.15 per cent after nine minutes. It remains nearly constant during the carbon reduction, and then becomes less than 0.1 per cent.

There is but little change in the carbon until most of the silicon is removed, when the curve drops rapidly, and the removal is practically complete in sixteen minutes. Up to this time there has been little change in the phosphorus. This is, of course, because the ferrous phosphate is reduced by carbon. From this point the removal of phosphorus is very rapid, being practically complete after the blow has continued twenty minutes.

The curve of sulphur was shown on the original diagram, but it was not copied, as the quantity of sulphur remained nearly constant, its value being less than 0.1 per cent. The blow ends at the twenty-minute line, and the curves beyond show the effect of introducing spiegeleisen.

Fig. 10 * gives the history of an acid Bessemer blow. The amount of silicon is very low for the acid process. Phosphorus remains practically constant at 0.1 per cent, and sulphur at 0.06 per cent. Figs. 9 and 10 are plotted on the same scale for comparison. The blow ends at 9 minutes 10 seconds, and the rest of the curve results from the introduction of spiegeleisen.

Open-hearth processes. — Steel is also made from pig iron in the hearth of a Siemens' regenerative furnace. (see Fig. 2). The silicon, manganese and carbon are removed by oxidation, as in the puddling, or in the Bes-

* Plotted from experiments of F. Julian at the South Chicago works of Illinois Steel Company. See H. M. Howe, *Journal Iron and Steel Institute*, Vol. 11, 1890, page 102.

semer, process. Two processes were formerly carried on in open-hearth furnaces: first, Siemens, or "pig and ore," process; second, Siemens-Martin, or "pig and scrap," process. These are combined into a single process in modern practice, and both scrap and ore are used.

In the Siemens process pig iron is charged into the hearth and melted, part of the silicon and manganese

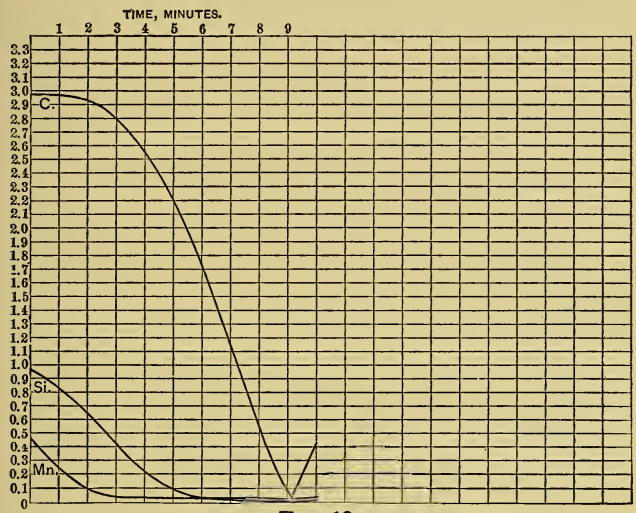


FIG. 10.

being oxidized during the melting, and then rich ore is added to supply the oxygen to combine with the remaining silicon and manganese, and the carbon of the iron carbide. When the action is complete the bath of nearly pure iron is recarburized by the addition of spiegeleisen or ferromanganese, and the manganese reduces the ferrous oxide present, and removes occluded gases or causes them to be dissolved, as in the Bessemer process.

In the Siemens-Martin process pig iron is charged into the hearth, and melted with partial removal of the silicon

and manganese, and then steel scrap is charged into the bath, which melts, and thus the percentage of silicon, manganese and carbon is reduced by **dilution.** The remaining part of these substances is removed by the direct action of the oxidizing flame, and the indirect action of the ferrous oxide formed at the surface of the bath, and mixed with it. Spiegel or ferro are added as in the Siemens process. Ferrosilicon and ferroaluminum are sometimes used in place of ferromanganese for the recarburization, the removal of iron oxide and the prevention of porosity.

Either acid or basic lining may be used in the furnace in which the open-hearth processes are carried on. With the acid lining no phosphorus is removed and hence low phosphorus pig must be used. With the basic lining the phosphorus is removed as in the basic Bessemer process.

Duplex process. — In modern practice in large steel plants the Bessemer converter and the open-hearth furnace are sometimes operated in combination. A charge is "blown" in an acid converter to remove silicon and manganese and a portion of the carbon; the charge is then transferred to a basic open hearth where the remainder of the carbon and the phosphorus are removed. This reduces the time in the open hearth and increases the output, and the converter may be lined with ganister, which is much cheaper and more durable than a basic lining. Another advantage is that the silica, formed by burning the silicon of the charge, is excluded from the basic furnace where phosphorus is removed, and hence does not need to be fluxed with lime; the result is economy of lime and increased durability of the open-hearth lining; this method also makes it possible to use a pig iron high both in silicon and phosphorus, which would be un-

desirable either in the basic converter or basic open hearth used separately, because of expense for lime and difficulty of slag disposal.

Ductile castings. — Many machine members of somewhat complicated form need to be strong and ductile. If such parts were required in large numbers, they could usually be produced by the process of casting, much cheaper than by the process of forging. For this reason much attention has been given to the production of ductile castings. The most important resulting processes are those for the production of malleable castings and steel castings. Some of the grades of brass and bronze give castings which are strong and ductile, but the high cost puts them out of competition for many purposes.

Malleable castings. — Castings of the required form are made of iron that cools with all of its carbon in the combined state. These castings, which have a white fracture, and are hard, weak and brittle, are packed in cast-iron boxes surrounded with coarsely divided oxide of iron, usually hematite ore or hammer scale. These boxes are sealed and brought to a temperature of full redness, from 1500° to 1600° F., as quickly as possible in a reverberatory oven and are held at this temperature at least 60 hours, and are then cooled very slowly, the slow cooling being quite important. Cast forms are thus produced that are very much like wrought iron in strength, ductility, resilience and softness. This process is called mallifying or annealing. Two changes occur to produce this result: first, the total carbon is reduced; second, the combined carbon is nearly all changed to graphitic carbon or "temper graphite," as it is called.

First change. — The reduction of total carbon in the mallifying process occurs chiefly near the surface of the casting. It is probable that, at the temperature of

mallifying, carbon of the surface iron unites with oxygen of the iron oxide, or with oxygen of the imprisoned air, forming gaseous carbon monoxide or carbon dioxide which passes off; there is then a tendency to movement of carbon from the inner portions of the casting toward the surface where it in turn may combine with oxygen and be removed.* The quantity of carbon thus removed must be a function of temperature, time of exposure to the decarbonizing conditions and of distance from the surface of the casting to the middle. Therefore, with a given time for annealing, thin castings might be quite transformed as to physical qualities, while thick castings might be only slightly changed. The removal of carbon by this means results in the formation of a surface layer which shows a wrought-iron-like fracture, while the rest of the fracture is black because of the second change. It is probable that migration of carbon occurs to only a slight extent in the ordinary American mallifying process.

Second change. — When molten cast iron with high carbon content cools under ordinary conditions, part of the combined carbon becomes graphitic carbon, appearing as flakes distributed throughout the cooled gray iron. The proportion of carbon thus becoming graphitic increases with the increase of total carbon, with the increase in time of cooling, with increase in silicon and decreases with increase in manganese; see page 127. But when iron contains less than 3 per cent of carbon with ordinary rate of cooling and with low silicon, the molten iron cools white, all carbon being in combination. If this white iron is raised to a temperature of from 1500° to 1600° F. as in the mallifying process, the combined carbon

* The fact of movement of carbon in solid iron at high temperatures is shown by the case-hardening process and by the cementation process; see pages 172 and 57.

tends to change into temper-graphite, and if the temperature is maintained long enough the change may be quite complete. The graphite thus produced takes the form of very minute particles nearly uniformly distributed, which interrupt the continuity of the iron structure much less than the graphite flakes in gray iron; its presence, therefore, has less effect to reduce strength and ductility than the graphite of the gray iron castings. During the change of combined carbon into temper graphite the resultant effect is to increase strength and ductility, because reduction of combined carbon has much greater influence in increasing these qualities than the presence of the temper graphite has to reduce them.

The first change is probably more effective in increasing ductility, but it can only be satisfactorily accomplished in light castings. The second change occurs in heavier castings and increases ductility, though in less degree than the first change. This may be made clearer by an experiment;* a casting having one portion about $\frac{3}{4}$ inch thick and another portion about $\frac{3}{16}$ inch thick was put through the mallifying process. Tests of the mallified castings for carbon showed results as follows:

Form of carbon	Thick part	Thin part
	Per cent	Per cent
Graphite	2.93	1.72
Combined carbon	0.04	0.20
Total carbon	2.97	1.92

There was a much greater reduction of total carbon in the thin part, but a more complete conversion of combined carbon into temper graphite in the thick part. The thin part was much more ductile than the thick part.

* This experiment was made at the works of the Westmoreland Malleable Iron Co.

During the early years of development and use of this process the iron for the castings was white pig iron from cold-blast charcoal furnaces, because low carbon and low silicon were necessary for success in the mallifying process. This iron was melted in regular foundry cupolas with very little chemical change. But in present practice gray pig iron from coke furnaces is melted in a reverberatory furnace, called an "air furnace," and the fluid iron is subjected to an oxidizing flame until silicon, manganese and carbon are reduced as low as is consistent with fluidity necessary for the production of "sharp" castings.

The changes that occur in very light castings during the mallifying process are shown by the following average results of several analyses:

Condition of castings	Total carbon	Graphitic carbon	Combined carbon
	Per cent	Per cent	Per cent
Before mallifying	2.79	0.177	2.613
After mallifying	1.74	1.565	0.175*

* Analyses made by Mr. W. H. McCord at the chemical laboratory of Stanford University.

Reduction of total carbon in the castings for the mallifying process is sometimes accomplished by charging steel or wrought-iron "scrap" into the cupola or air furnace; this reduces the carbon by **dilution.**

Long experience has shown that the iron charged into the air furnace should contain about the following percentages of the substances given:

	Per cent
Silicon	1.25
Manganese	0.40
Phosphorus	0.15 to 0.2
Sulphur, not over	0.05
Carbon	3.5.

In the furnace the silicon is reduced to from 0.7 per cent to 1 per cent; manganese and sulphur are only slightly changed, while carbon is reduced to about 2.75 per cent. The phosphorus is not removed, but its presence in nearly the specified amount is desirable, because it renders the molten iron more fluid for casting and does not harm the product.

If it is necessary to heat malleable castings for any purpose, as for straightening or bending, great care is necessary because, if the temperature is raised much above the mallifying temperature, from 1500° to 1600° F. the temper graphite combines again with the iron and the castings become brittle as they were before mallifying.

Steel castings. — Some cast machine members need to be stronger and more ductile than malleable castings; other cast machine members are too thick to mallify satisfactorily. To meet such cases steel castings are made by pouring molten steel into molds directly from the steel-making process. When this is done the steel foundry includes **steel making** as well as **steel founding.**

Converters and open-hearth furnaces are used in steel foundries though they are usually somewhat smaller than those producing steel ingots in steel mills. Special converters are used like the Tropenas or the Stoughton types.* In these converters all or part of the air enters above the surface of the metal bath and oxidation of the substances to be removed occurs by direct combination with oxygen of the air and by indirect combination with the oxygen of the iron oxide, which is formed and mixed with the bath and reduced again throughout the blow. Obviously, the carbon is burned to carbon dioxide (see page 64) and the entire heat of combustion of the carbon is util-

* See " The Metallurgy of Iron and Steel " by Bradley Stoughton; McGraw-Hill Book Co., page 272.

ized to help fix the temperature of the bath through the necessary range.

Reheating and working of steel ingots by mill processes improves strength and ductility; but steel castings do not get the benefit of this improving process, and hence, the pig iron used for making steel for castings must be lower in sulphur, and in phosphorus also if the acid process is used, than that used for ingots, in order that the castings may equal the forgings, made from the ingots, in strength and ductility. This means a more expensive pig iron, which adds to the cost of the steel castings.

Basic steel is more apt to have porous spots and "blow holes" when cast than acid steel,* and these defects are especially undesirable in steel castings, because they cannot be welded up as in ingots. They may be a hidden source of weakness in stress members; and often much useless expense for labor is incurred when a "last cut" reveals porous defects that lead to the rejection of a nearly finished casting. The presence of manganese or silica tends to prevent porosity, and one or other of these substances is introduced in the recarburization; but it is difficult to hold silicon from oxidization during "teeming" or casting, which occupies more time for steel castings than for ingots, and if manganese is introduced in sufficient quantities to protect the iron from oxidation it may appear in the product in sufficient quantity to cause weakness and brittleness.

To avoid porosity and brittleness, due to the presence of oxygen or iron oxide, a small amount of pure aluminum is sometimes introduced into the melt before pouring; the aluminum combines with the oxygen and is almost entirely removed in the slag.

Steel for castings is sometimes obtained by melting

* See page 63.

proper mixtures in crucibles. Obviously the fuel and labor cost is higher, but in the castings there is less liability of formation of blow holes, and it is easier to control the content of substances other than iron than in the open-hearth or the converter.

Steel that is cooled from a molten state has a rather coarse crystalline structure; this can be transformed into a fine structure with accompanying gain in strength and ductility by reheating and rolling or hammering at suitable temperatures (see page 171) or by suitable heat treatment without mechanical working (see page 168). In case of steel castings the refining of structure must, of course, be accomplished without mechanical working.

Steel for castings must be poured hotter than steel for ingots, since in the former case the metal must "run sharp," in order to take the required form in the mold, whereas this is of little importance in the case of ingots. Because of this, higher grade refractory material is needed for the linings in the steel foundry, and cost of furnace repairs is higher, than in the steel mill.

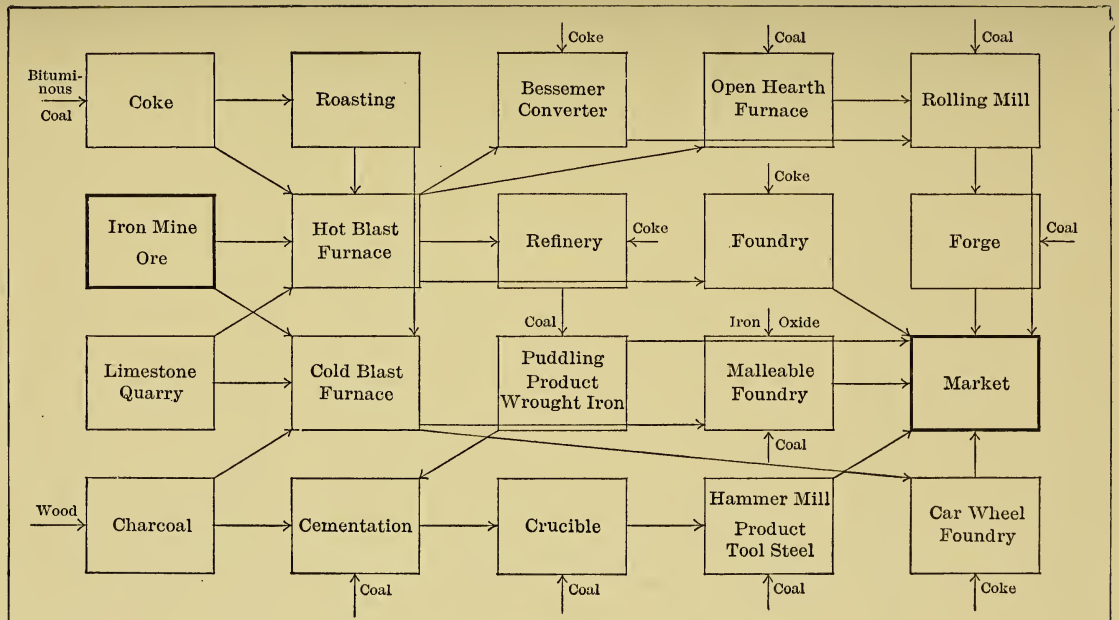
The molds for steel castings are made both of "green sand" and of "dry sand"; but the sand in either case must be more refractory than that used in molds for iron castings, because the casting temperature of steel is probably from 2800° F. to 3000° F., while that for cast iron is about 2400° F.

There is probably a difference of about 400° F. or 500° F. between the temperatures of solidification of steel and cast iron, and, since solid shrinkage begins when solidification is complete, it follows that shrinkage is greater in steel, and, therefore, greater care must be taken both in the design of the steel castings and in the regulation of the rate of cooling of different parts of the casting that have different thickness of cross section. The shrink-

age stresses are removed if the casting is reheated for heat treatment to refine structure. See page 168.

Steel castings, like steel ingots, are made with varying carbon content to meet the varying demand for strength, ductility and capacity for shock resistance. Increase in **strength** obtained by increase in carbon is accompanied by reduction of **ductility;** the converse also is true. **Shock resistance** increases both with strength and ductility, but the increase is greater with ductility than with strength, and therefore there is usually a resultant increase in shock resistance with reduction of carbon.

Steel castings contain from 0.15 per cent to 0.7 per cent of carbon according to the required service. About 0.1 per cent to 0.35 per cent of silicon is usually present, the lower value for soft castings and the higher value for hard castings. This amount of silicon does not diminish toughness of the metal itself and its presence seems to reduce the amount of iron oxide and free oxygen present with their undesirable effects. Sulphur and phosphorus should be kept below 0.05 per cent in castings that are to be subjected to severe stress.



FROM MINE TO MARKET.

CHAPTER V

OUTLINE OF THE METALLURGY OF COPPER,* LEAD, TIN, ZINC AND ALUMINUM

Copper is found in nature as native or pure copper, and in combination with many other substances. The only combinations that are of commercial importance are sulphides, oxides, carbonates and silicates. Whether the copper is pure or combined it is usually mixed with earthy "gangue," the amount of copper present varying from less than one per cent to 15 per cent or more.

Copper is obtained from its ores either, (1) by "wet methods," or hydrometallurgy, or (2) by "dry methods," or smelting. In (1) the copper is taken up by some solvent and leached out of the ore, the gangue remaining practically unchanged; in (2) there is partial separation of the metallic combinations from the gangue by reason of specific gravity, (*a*) without application of heat; or (*b*) with the ore in a molten state. Only dry methods, which produce over 90 per cent of the copper of commerce, will be considered here.

The copper that is produced by these methods is usually quite impure and must be refined either by the smelting refining or the electrolytic refining process, or by both.

Native copper. — The ore of the Lake Superior district contains from 0.5 per cent to 4 per cent of copper

* For fuller treatment of this subject see "Practice of Copper Smelting" by Peters and "The Metallurgy of the Common Metals" by Austin.

rather finely divided and distributed throughout the earthy material of wide lodes. This ore is concentrated without heat until the copper becomes from 30 per cent to 90 per cent or more of the "mineral" as the concentrate is called. Ore from the mine is crushed and passed through steam stamps and then through a series of "jigs," where it is shaken to help separation by gravity, and where a stream of water washes away the lighter portions from the upper surface, leaving the concentrated mineral.

This mineral is smelted in a reverberatory furnace where a fusible slag is formed either by proper mixture of mineral with different gangue content, or by introduction of a suitable flux. Again gravity carries the heavier metal down and the fluid slag is removed and the copper is cast into ingots.

Oxides, carbonates and silicates of copper. These ores are found in the upper portions of mineral deposits, having been formed by the decomposition of copper sulphides through the agency of air and water. The smelting of such ores may be accomplished in a furnace of the blast-furnace type, the carbon dioxide of carbonates being driven off by heat, the oxide of copper being reduced by carbon monoxide from the fuel, and the silica of silicates being removed in the slag. The gangue enters the slag, which is made fusible by proper mixture of ores or by the introduction of a flux. Molten slag and molten copper are drawn off at proper intervals. The copper loss in the slag in this process is large, because copper oxide combines with the silica, and because some metallic copper is carried away mechanically. This process is not very extensively used now because of growing scarcity of oxide ores, and also because it is advantageous to charge oxide ores with sulphide ores to help supply the necessary oxygen for the removal of sulphur as sulphur dioxide.

Copper sulphide ores. — The sulphide ores of copper contain not only copper sulphide but also iron sulphide together with the gangue. If such ore is melted in a neutral or reducing atmosphere the copper and iron sulphide will melt into a "matte" which settles out of the ore by gravity, leaving the gangue which, if properly fluxed, may be drawn off. No sulphur is removed by this treatment; but if the ore is first roasted in an oxidizing atmosphere at a temperature too low to melt the sulphides, part of the sulphur will burn and pass off as the gas SO_2. Copper holds sulphur more strongly than iron does, and hence the iron sulphide yields its sulphur first and the iron deprived of its sulphur takes up oxygen. The product of carefully regulated roasting contains copper sulphide, iron oxide and silicious gangue; probably some copper oxide has been formed and some iron sulphide remains. When this product is smelted the copper and iron sulphides melt, carrying down any precious metals that may be present; the iron oxide acts as a flux for the silicious gangue, thus forming a fusible, removable slag while any iron sulphide present enters the matte which is drawn off and cooled as "coarse metal." In this process silica sometimes has to be added as a flux when the ore carries excess of iron and the gangue is deficient in silica. The roasting and smelting are repeated until all iron and gangue are removed and only copper sulphide, or "fine metal," remains. This fine metal is cooled in proper form and size and is roasted in an oxidizing atmosphere; a part of the sulphur burns, while the copper thus freed from sulphur takes up oxygen, forming copper oxide. When this roasting has continued long enough to produce the right proportions of copper oxide and copper sulphide, the charge is melted and copper oxide gives up its oxygen to combine with the sulphur of the copper sulphide, pro-

ducing sulphur dioxide which passes off as a gas, leaving metallic copper.

Blister copper, or black copper, the product of the three processes described, still contains substances that reduce value for industrial purposes; sulphur, iron and copper oxide are present; and there often are precious metals, gold, silver or platinum, that may be removed with profit; and often antimony, arsenic, bismuth, selenium and tellurium. These five substances, if present in the ore, are not entirely removed by the roasting or smelting processes. There are two refining processes: furnace refining and electrolytic refining. If it is found from analysis that precious metals are present in amounts that will make their recovery profitable, the furnace refining may be omitted and the copper cast into anode plates which are transferred to the electrolytic refinery: here they are suspended in an electrolyte consisting of a solution of copper sulphate in dilute sulphuric acid. A suitable current is maintained through the solution and the copper is transferred, through the agency of the electric energy, from the anode to the cathode, where it is deposited free from impurities. The precious metals, together with the other substances carried by the anode plates, fall to the bottom of the tank containing the electrolyte, forming "slimes" which are treated for the recovery of the precious metals, while the pure copper from the cathodes is prepared for the market.

But if there is not a profitable content of precious metals the refining may be done by the furnace method. The blister copper is melted down in a reverberatory furnace, a slag forming during the melting, which is probably composed of silica present, and iron oxide formed during the melting; this slag is skimmed off and compressed air is forced through the bath of molten metal; the result is

that sulphur, arsenic, iron and copper are oxidized; the oxidized sulphur and arsenic pass off as gas, and the iron oxide combines with the remaining silica to form additional fusible slag, which is removed. Some of the copper oxide formed acts as a carrier of oxygen, yielding its oxygen to combine with sulphur of any copper sulphide that remains; but a considerable amount of copper oxide is left in the bath after the removal of impurities is complete. The oxidizing atmosphere is now changed to a reducing atmosphere and green poles, branches of trees, are inserted so that the ends dip beneath the surface of the bath of molten copper; the evolution of steam and gas agitates the bath and the carbon of the charred poles combines with the oxygen of the oxide of copper and forms carbon monoxide, leaving the pure copper, which is cast into ingots.

Lead. — Many combinations of lead with other substances occur in nature, but almost the entire supply of lead of commerce is obtained from the ore **galena** which consists of lead sulphide mixed with varying proportions of gangue. Sometimes the galena also bears silver and, more rarely, gold, while copper, antimony and arsenic are commonly present. If the ore does not contain paying proportions of silver or gold, it may be concentrated without heat by stamping and washing before melting. But if these precious metals are to be extracted no preliminary concentration is allowable because of loss of the precious metals in the gangue removed.

Treatment of Galena. Roasting. — Crushed ore is charged into a reverberatory furnace and a low temperature is maintained in an oxidizing atmosphere. The sulphur of a part of the lead sulphide, PbS, is oxidized and passes off as sulphur dioxide, SO_2, while the lead that is left takes up oxygen, forming lead oxide, PbO; also

some lead sulphate, $PbSO_4$, is formed by oxidation of lead sulphide. These changes may be represented thus:

$$PbS + 3O = PbO + SO_2.$$
$$PbS + 4O = PbSO_4.$$

Smelting. — After the roasting has continued long enough to produce proper proportions, the lead oxide and sulphate are mixed with the remaining lead sulphide, the temperature is raised in a neutral atmosphere and the following reactions take place:

$$PbS + 2\,PbO = 3\,Pb + SO_2.$$
$$PbS + PbSO_4 = 2\,Pb + 2\,SO_2.$$

The metallic lead melts and settles in a low part of the furnace, whence it is cast into ingots. The remainder of the charge still contains a large amount of lead, and the roasting and smelting are repeated several times; ultimately no lead sulphide is left to reduce the remaining lead oxide and sulphate. Then fine carbon (coal) is introduced with the charge to take away oxygen in gaseous CO_2 from the lead oxide, and to reduce lead sulphate to sulphide, thus rendering the sulphur also available as a reacting agent. Thus an additional amount of lead is freed, melted and cast into ingots. During the smelting lime is added to render the charge more resistant to melting, since it is desirable to melt the lead out from the solid residue. In this residue there still remains a considerable amount of lead, probably as oxide or sulphate, which cannot be removed by repetition of roasting and smelting; the amount may run as high as 30 per cent. Transfer may then be made to a blast-furnace for lead smelting where most of the lead may be recovered. Each of the successive smelting processes has a higher temperature than the preceding one and produces less pure lead.

This process is not suited to ores containing more than 5 per cent of silica, since silica unites with lead oxide, causing loss of lead in the slag. Other forms of furnace are used for smelting lead, but the chemical changes are the same as those given, the difference being in the details of operation.

Ores containing lead, silver and gold, and usually copper, arsenic and antimony are smelted in a blast-furnace, an important function of the lead being to collect and carry down the precious metals into the "base bullion." Oxide ores of lead may be used directly, but sulphide ores are roasted so that the resulting oxide may be reduced by CO of the blast-furnace; some sulphide remains, however, in the roasted ore. The flux used is iron ore and limestone, and the ferric oxide, reduced to ferrous oxide, also acts with carbon to reduce the lead sulphide, as follows:

$$PbS + FeO + C = Pb + FeS + CO$$

and also to reduce the lead sulphate as follows:

$$PbSO_4 + FeO + 5\,C = Pb + FeS + 5\,CO.$$

The molten lead not only carries down gold and silver, but also copper, arsenic and antimony. The remaining FeO unites with lime of the flux and the silica of the gangue to form a fusible slag.

Softening. — The base bullion from the blast-furnace is treated first in a shallow reverberatory furnace, where it is melted and subjected, in an oxidizing atmosphere, to heat at a temperature that just melts the lead. At the surface lead, copper, antimony and arsenic oxidize and combine into a "dross" which floats upon the molten lead. This process is continued until tests show complete removal of the copper, arsenic and antimony. Then the charge is cooled just enough to harden the dross

which is skimmed off; the lead now contains only silver and gold, and is treated by the Pattinson process.

The Pattinson process depends upon the fact that when a molten mixture of lead and silver is cooled slowly with constant stirring, crystals of lead very low in silver will form, and removal of these crystals leaves lead high in silver. This process is carried out in a series of cast-iron pots set in masonry with properly arranged furnaces for heating. Lead containing silver is melted in the first pot and then the source of heat is withdrawn; as the stirred metal cools the crystals of lead very low in silver are dipped into the second pot by means of a skimmer that allows the molten metal richer in silver to run back into the first pot. Extension of the process eventually gives lead very high in silver in the first pot and lead very low in silver in the last pot. The latter goes to the lead market, while the former is treated in the **cupellation furnace,** where the lead is all oxidized into PbO, litharge, leaving purified silver. Then the PbO is reduced by carbon monoxide in a reverberatory furnace, leaving pure lead.

The Pattinson process leaves copper, arsenic and antimony with the silver and hence produces a very pure, soft lead.

Tin. — Nearly all the tin of commerce is extracted from the ore called "tinstone" or "cassiterite," which consists of a stannic oxide, SnO_2, mixed with gangue containing earthy and metallic substances.

For removal of the earthy portion of the gangue the ore is stamped fine and washed on racks, where a stream of water carries away the lighter material from the surface, leaving the tin oxide and other heavy material. This concentrated ore, which usually contains iron and copper pyrites, FeS_2 and $CuFeS_2$, and arsenical pyrites, FeSAs, is

roasted in an oxidizing atmosphere in a reverberatory furnace. Sulphur is removed as gaseous SO_2; arsenic forms the oxide, As_2O_3, the white arsenic of commerce, which is caught in long flues; while the copper becomes copper oxide and copper sulphate, and the iron becomes iron oxide. The soluble copper sulphate is removed from the roasted ore by washing. The washed ore, which still contains copper, iron, arsenic and sulphur, is then reduced by smelting with carbon in small shaft furnaces or in reverberatory furnaces. In either case oxygen of the tin oxide combines to form carbon dioxide either with carbon mixed directly with the ore, or with carbon monoxide from partial combustion of coal used as a source of heat. A small amount of lime is used as a flux to remove silica that may remain. The ingots of crude or raw tin from the smelting process still carry not only copper, iron, arsenic and sulphur but often also lead, antimony and tungsten, which must be removed by refining. This refining usually consists of two processes, liquation and boiling. The ingots of crude tin are piled on the hearth of a reverberatory furnace and the temperature is slowly increased to a point where the tin melts out leaving the unfused impurities. The molten tin, still with small amounts of iron, arsenic and sulphur, is led into a receptacle, which has a separate source of heat, where green twigs in bundles, or wet sticks, are held submerged in the bath of tin. Evolution of steam and gas causes brisk agitation of the tin, whereby all parts are brought in contact with the air and the impurities are oxidized. A scum of a portion of the oxides thus formed collects on the surface. After the boiling, the still molten metal is allowed to stand for about an hour, when the scum is removed and the tin is ladled out into ingot molds. A part of the oxidized impurities goes out with the scum, but another part which is of higher

specific gravity than the tin settles toward the bottom. Thus, when the tin is ladled out, that which comes from the top, called "refined tin," is purer than the so-called "common tin" from the lower portions of the mass. The material at the bottom is often cooled and liquated and boiled again.

The residue in the liquation furnace with increased temperature yields more tin of lower grade.

Sometimes a process called "tossing" is substituted for boiling; the molten tin is dipped in ladles and allowed to run back into the bath from a considerable height.

There are effective methods for recovering a large portion of the tin which remains in the smelter slags and in refining dross.

Zinc. — The ores from which zinc of commerce is extracted are:

Zinc blende, which consists of zinc sulphide, ZnS, mixed with earthy gangue and usually with manganese, iron, cadmium and silver; more rarely it bears mercury, gold, lead and tin.

Calamine, made up of zinc carbonate, $ZnCO_3$, with cadmium, iron and manganese as carbonates, and with lead sulphide and iron oxide, and earthy gangue. Zinc silicate, Zn_2SiO_4, is also sometimes present.

Franklinite, which is made up of oxides of iron, manganese and zinc with earthy gangue.

Zinc vaporizes at a temperature of about 1725° F. and advantage is taken of this fact in smelting. Zinc oxide and coal, both finely divided, are mixed and heated in muffles or retorts, where the zinc oxide is reduced by the carbon with formation of carbon monoxide, and where the metallic zinc is vaporized, led away and condensed.

Since the ore for this purpose must be in the form of zinc oxide, it is necessary to roast the ores containing

zinc sulphide — zinc blende — in an oxidizing atmosphere to oxidize and remove the sulphur as SO_2 and to oxidize the zinc.

Zinc carbonate ore — calamine — is usually roasted to remove moisture and to drive off carbon dioxide from the carbonate in order to produce the zinc oxide for smelting.

The **Belgian process** for smelting zinc is chiefly used in the United States. Retorts, which are refractory cylinders about $8\frac{1}{2}$ inches in diameter and four feet long (see Fig. 11) are set in tiers in a chamber having a source of heat. The inner end of the retort is closed, and a refractory cone *C* is inserted in the outer open end. The retorts are charged with the fine mixture of coal and zinc ore, usually moistened so as to cohere, and the heat from the furnace raises the temperature of the charge. Water is driven off as steam which passes out through the cone. The carbon of the coal unites with the oxygen of the zinc oxide forming carbon monoxide which passes through the outer opening of the cone where it burns — with a blue flame — to carbon dioxide. The zinc thus isolated is vaporized and the vapor passes to the cone where, on meeting the cooler walls, it is condensed and the liquid zinc is withdrawn at proper intervals. When the charge is exhausted the cone is removed, the residue is withdrawn, the retort is recharged, the cone is replaced and the process begins again.

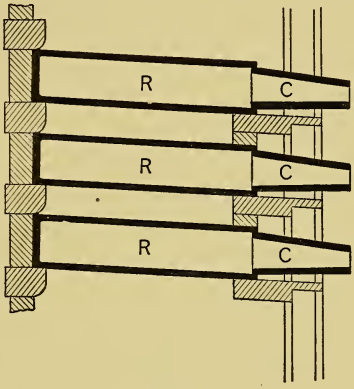


Fig. 11.

Aluminum. — Aluminum occurs very abundantly in nature, but it is always in combination with other substances, such as oxygen, sodium, fluorine and silicon.

In its combinations with silicon and oxygen, aluminum is useful for refractories and in the ceramic arts. See Chapter III.

Metallic aluminum may be produced by several methods, but the most important process commercially is electrolysis, or decomposition by an electric current, of alumina, Al_2O_3. Pure alumina is very infusible; and, since a substance must be fluid for electrolysis, it was necessary to find a solvent for alumina that would melt at a relatively low temperature, and that would allow the decomposition of the alumina without being affected itself. In 1889 a patent was granted to Charles M. Hall, covering the use of cryolite, a fluoride of aluminum and sodium, $3\,NaF,\,AlF_3$, as a solvent bath for electrolysis of alumina. This substance melts at a red heat, and when melted dissolves alumina, thus forming an electrolyte which can be decomposed by a suitable electric current.

The process is carried out in rectangular cast-iron pots having a lining of hard-baked carbon about 3 inches thick which forms the negative electrode or cathode. The positive electrodes or anodes consist of cylindrical carbons about 3 inches in diameter and originally about 15 inches long; these are suspended with axes vertical by $\frac{3}{8}$-inch rods of copper, which in turn are clamped to a copper bar that extends above the pot throughout its entire length. This bar and the carbon lining of the pot are connected into a current to which electrical energy is supplied at low voltage. The anodes are lowered until they touch the cathode which is the lining of the pot. This completes the circuit and electricity flows. The anodes are then withdrawn slightly to form an air gap,

thus providing an electric furnace of the arc type. Cryolite for the solvent bath is then introduced and is melted by the heat from the electrical energy supplied. Pure alumina is then stirred into the bath and electrolysis begins. The Al_2O_3 is decomposed by the action of the current, aluminum being deposited on the cathode or pot lining, while oxygen appears at the surface of the anodes, combines with the anode carbon and passes off as gaseous carbon dioxide, thus causing the anodes to waste away and to require periodical renewal. The metallic aluminum is dipped or syphoned out at intervals and cast into ingots.

The alumina for this process must be free from other substances; and, since pure alumina is not found in nature, a purification process is necessary. The source of the alumina is usually bauxite, which has already been described (see page 34) as a "mixture of a large proportion of hydrated alumina, $Al_2O_3 \cdot 2\ H_2O$, with clay, silica, iron oxide and titanic oxide and often with another hydrated aluminum oxide, $Al_2O_3 \cdot 3\ H_2O$." The separation of the alumina from the other substances of the bauxite is effected as follows:

The bauxite is ground fine and mixed with fine sodium carbonate; the mixture is stirred and heated in a furnace and the alumina displaces the carbon dioxide of the sodium carbonate, driving off the gaseous carbon dioxide and forming aluminate of soda. This may be expressed chemically as follows:

$$Al_2O_3 \cdot 3\ H_2O + 3\ Na_2CO_3 = Al_2O_3 \cdot 3\ Na_2O + 3\ CO_2 + 3\ H_2O.$$

The aluminate of soda thus formed is soluble in water, while the other substances in the bauxite remain unchanged and are insoluble. When the reaction is shown by chemical tests to be complete the charge is withdrawn

and cooled and the aluminate of soda is taken into solution in warm water and thus separated from the undesirable substances. Then carbon dioxide is forced through the solution of aluminate of soda and soluble sodium carbonate is formed, and the alumina which is precipitated is filtered out, washed and dried and is ready for electrolysis. The sodium carbonate is recovered to use again in the process.

Alumina is also obtained by making an intimate mixture of very fine **cryolite** with calcium carbonate (chalk) and roasting the mixture; the chemical reaction is as follows:

$$2\,(AlF_3 \cdot 3\,NaF) + 6\,CaCO_3 = Al_2O_3 \cdot 3\,Na_2O + 6\,CaF_2 + 6\,CO_2.$$

The products are gaseous carbon dioxide, insoluble calcium fluoride and aluminate of soda, which may be dissolved and treated as in the last process to produce pure alumina.

PART SECOND — PHYSICAL PROPERTIES OF MATERIALS

CHAPTER VI

TESTING MATERIALS

Machine members in service are subjected to the action of external forces which tend to break or distort them. Some members, like springs, fulfill their function by yielding periodically through considerable space to applied forces; but a large proportion of members require rigidity, that is, the yielding under applied forces must be kept very small. In any case **permanent** distortion and breakage must be prevented.

The designer of machines must know the effect of external forces applied to the materials of machines. This knowledge is derived from tests. A test piece of suitable dimensions may be made of any material and a steadily increasing force may be applied to it until it breaks or is very much deformed. The force applied to the test piece may tend to crush it, a compressive force, or to pull it apart, a tensile force, or to bend it, a transverse force, or to twist it, a torsional force, or the external forces may produce some combination of these tendencies.

A solid resists change of form; forces applied to a solid tending to change its form induce stress within it; **stress** may be defined as the action and reaction between adjacent parts of a solid during resistance to change of form.

First illustration. In Fig. 12, suppose the tensile force P is applied to a cylindrical test piece; in any cross section like AA there will result an action and reaction between adjacent faces of the section resisting separation; this action and reaction is called **tensile stress.** If P equals

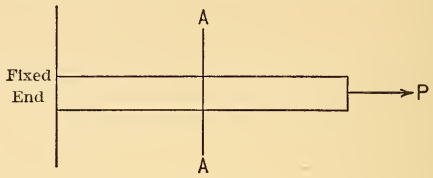


Fig. 12.

5000 pounds the **total stress** in the section AA is 5000 pounds; if the cross-sectional area of AA equals one square inch the **unit stress** in the section is 5000 pounds per square inch. If the area of cross section were $\frac{1}{2}$ square inch, the unit stress would equal $5000 \div \frac{1}{2} = 10{,}000$ pounds per square inch. Reversal of the direction of the external force P would change it from a tensile force to a compressive force tending to crush the test piece, and in all sections like AA a **compressive stress** would result.

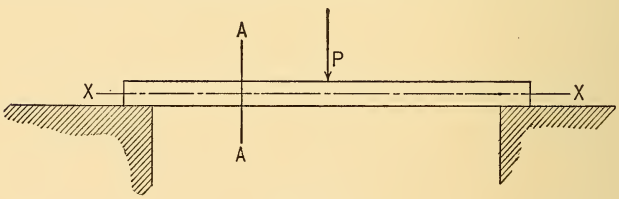


Fig. 13.

Second illustration. In Fig. 13, suppose a transverse force P applied tending to bend a test piece of rectangular cross section. If the test piece is bent by this force, the fibers below a neutral axis XX would be stretched, while

those above would be shortened; hence the bending force would produce in any section both tensile and compressive stress. Also the force P tends to cause the adjacent surfaces in any section like AA to slide over each other and thus there is produced **shearing stress** in the section.

Third illustration. The test piece may be subjected to a force that tends to twist it about its axis, as in Fig. 14. Then in any section AA there is a tendency for one surface to slide over the adjacent surface about the axis of the test piece, and hence **shearing stress** is induced.

Testing machines have been designed and constructed

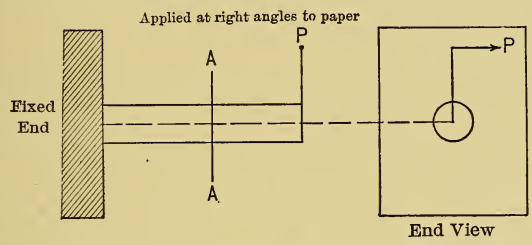


FIG. 14.

capable of applying definite forces to test pieces in these several ways,* with devices for measuring the **deformation** corresponding to any applied force. In whatever way the force is applied to the test piece the object of the test is to record **simultaneous values of stress** and **deformation,** because a knowledge of the relation of these values enables the designer to proportion machine parts for safety from breakage, for necessary rigidity in operation, and for economy of material.

A tension test of ductile material will now be considered for illustration. The increasing tensile force P is

* See "Experimental Engineering," by Carpenter and Diederichs, Chapter IV.

applied as in Fig. 12 and the resulting change of form — deformation — is elongation, accompanied by corresponding reduction of section area. Assume that P is applied in successive increments; there will be corresponding values of p, representing unit stress in any cross section, and, if the **original section area** is represented by F, the successive values of p will equal the corresponding values of $P \div F$.*

Assume also that after each increment of stress an accurate measurement of elongation is made. In the early part of the test the elongation is proportional to stress; but after passing a certain limit, called the **elastic limit,** the elongation becomes increasingly greater for a given increase in stress. The law may be stated thus: **deformation is proportional to stress within the elastic limit.**

If, before reaching the elastic limit, the stress is gradually reduced to zero, the elongation becomes zero also; that is, the test piece returns to its original dimensions. Within this limit the material may be considered perfectly elastic,† since **elasticity** may be defined as **the property whereby a material returns to its original dimensions on relief of stress.** If, however, the elastic limit is passed before relief of stress, the test piece will be permanently elongated. This permanent elongation

* Since F decreases with increase of P the successive values of p strictly should equal the corresponding values of P divided by the corresponding values of varying F. In practice, however, F is considered constant and equal to the original section area.

† It is probable that even within the elastic limit the material is not perfectly elastic. Very refined measurements show that materials take some "set" even under relatively small stress. The values of this set, however, are so very small that they may be safely disregarded in the ordinary testing of the materials of engineering.

is called "**set.**" The elongation that disappears on relief of stress is called **elastic deformation.**

After passing the elastic limit the elongation accompanying a given increment of stress increases steadily until finally the **maximum stress** that the test piece is capable of sustaining is reached and rupture occurs. This maximum stress is a measure of the **ultimate strength** of the material.

If the test piece were divided into equal units of length, say one inch, as in Fig. 15, and if the material were absolutely homogeneous and of equal strength in all sections, it would follow that with increasing stress all units of length would share equally in the elongation

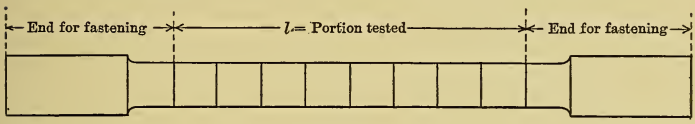


FIG. 15.

and, on reaching a stress corresponding to the ultimate strength of the material, all sections would yield at once. But no such material is available for machine parts and when the ultimate strength of the **weakest section** is reached, local yielding occurs, a "neck" forms and the piece breaks.

Fig. 16 shows a tension test piece before and after testing. The original piece is subdivided equally by punch marks into half-inch units of length. The tested piece shows the increase in length of these units, and also the local reduction of area and fracture at minimum section.

As the test goes on the equal divisions, see Fig. 15, share the elongation almost equally until maximum stress is reached. At any point in the test there is a total elongation represented by λ expressed in inches and there

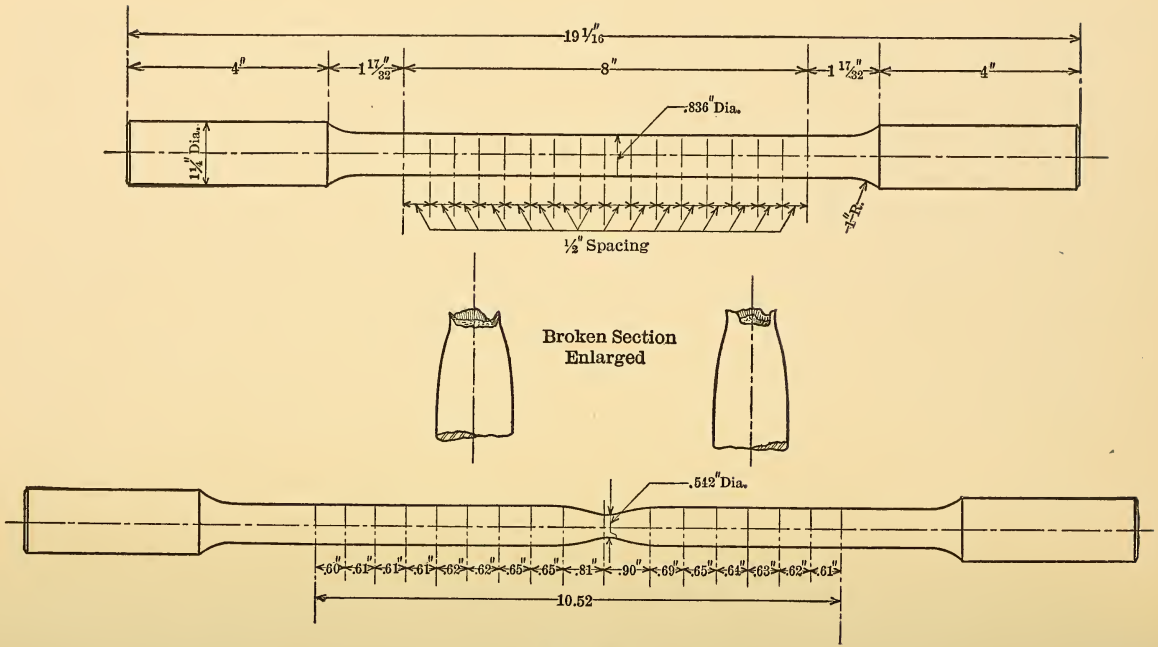

19 1/16"
4"
1 17/32"
8"
1 17/32"
4"
.836" Dia.
1 1/4" Dia.
1" R.
1/2" Spacing
Broken Section
Enlarged
.512" Dia.
.60" .61" .61" .61" .62" .62" .65" .65" .81" .90" .69" .65" .64" .63" .62" .61"
10.52

FIG. 16.

is a corresponding unit elongation (or elongation of each of the one-inch divisions) represented by ϵ, and expressed in inches per inch of original length l, of the tested section. It follows then that

$$\epsilon = \frac{\lambda}{l}.$$

After passing the maximum stress the elongation and reduction of section area are localized at or near the neck.

The simultaneous values of unit stress p and of relative elongation ϵ may be plotted with reference to rectangular axes (p values being laid off vertically upward and ϵ values being laid off horizontally toward the right) and through the points thus located a curve may be drawn called the **stress-deformation diagram.** In what follows, this name will be abbreviated to **s.-d. diagram.**

Fig. 17 shows s.-d. diagrams for mild steel. Diagram I is plotted on such a scale for X values that the entire diagram up to breaking falls within the limits of the figure. The yielding, however, on this scale is too small to show until a unit stress of nearly 33,000 pounds is reached. Hence diagram II is plotted with greatly increased scale for values of ϵ, and this diagram shows the test only as far as M, diagram I. This diagram is useful as showing more clearly what occurs in the early part of the test.

Starting from A with stress and deformation equal to zero the line of the diagram is straight until B_1 is reached. This point B_1 is the elastic limit which is strictly defined as **the point where proportionality of stress and deformation ceases;** or, otherwise expressed, it is the point where the diagram line ceases to be a straight line. Usually in ductile materials the diagram line then curves to the right until the **yield point** is reached, where it becomes

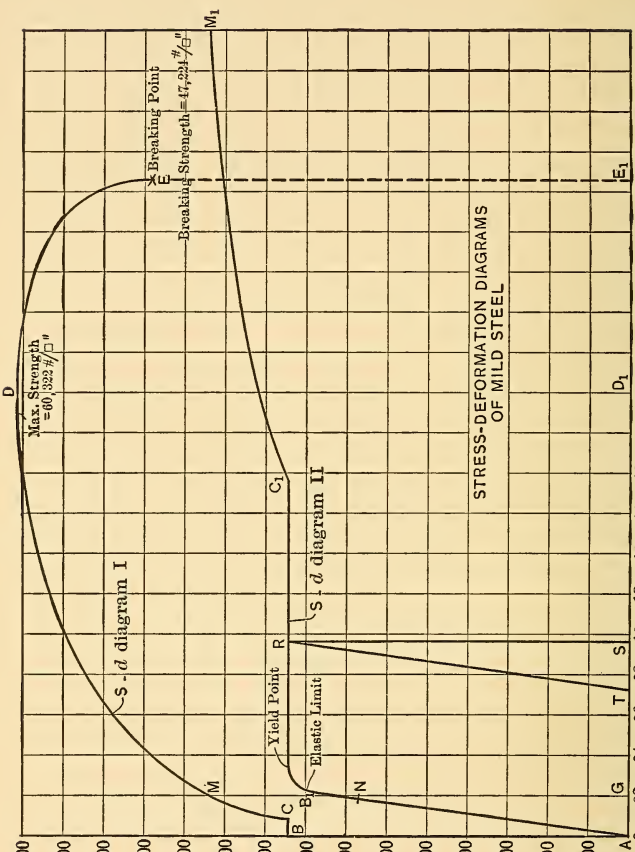

STRESS-DEFORMATION DIAGRAMS
OF MILD STEEL
Stresses in Pounds per Square Inch
Elongations $\frac{l-l_0}{l_0}$ = ε
Scale for s, d diagram I
s, d diagram I
s, d diagram II
Max. Strength
=60,322 #/□"
Breaking Point
Breaking Strength=47,224 #/□"
Yield Point
Elastic Limit
A
B
B₁
C
C₁
D
E
E₁
M
M₁
N
R
S
T
G
D₁
60 000
56 000
52 000
48 000
44 000
40 000
36 000
32 000
28 000
24 000
20 000
16 000
12 000
8 000
4 000
0
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
.26
.28
.30
.32
.34
.36
.38
.40

FIG. 17.

about horizontal, indicating a considerable yielding without increase of stress.* At C_1 further elongation requires increase of stress and the diagram line rises in a curve to M. In engineering testing the yield point is usually taken at the elastic limit.

If on reaching some point within the elastic limit, N, for example, stress had been reduced gradually to zero, the point tracing the diagram line would have retraced the line to A, and the test piece would have recovered its original dimensions.

But if the relief of stress had been delayed until some point beyond the elastic limit R was reached, the tracing point would return to the X axis over the line RT nearly parallel to B_1A. During this return a certain portion of the elongation (**elastic deformation**) ST would disappear, while another portion, TA, would remain as **permanent set.**

The physical properties that appear on the s.-d. diagram are:

1. Strength at elastic limit.
2. Strength, ultimate.
3. Ductility.
4. Elasticity.
5. Stiffness.
6. Resilience, elastic.
7. Resilience, ultimate.

1. The **strength at elastic limit** is proportional to the ordinate AB, whose value may be read in pounds per square inch.

2. The ultimate strength is proportional to the maximum ordinate DD_1, whose value in pounds per square inch may also be read.

* For an explanation of the probable reason for the horizontal part of the diagram line, see page 155.

3. A material is ductile that stretches under an increasing tensile force before it breaks. **Ductility** is therefore proportional to the amount of stretching. Hence it is proportional to the length of the s.-d. diagram on the axis of X. If s.-d. diagrams of different materials are plotted with the same scale for values of ϵ, the relation of their ductilities can be found by comparison of the lengths of the diagrams on the X axis. The value of ϵ at rupture might be taken as a measure of ductility; but in engineering test practice it is customary to measure the elongation of the tested section of the test piece after rupture, and to compare this with the original length of the tested section. Ductility is thus expressed as per cent elongation in l inches, l being original length of tested section. It is necessary to specify the original length because, from the maximum stress until rupture, the elongation is localized and is not shared by all one-inch sections alike, hence the **average** elongation depends on how many of the unnecked sections are included with the necked section in finding the average. For example, the average elongation derived from the necked section taken with two other sections would be greater than the value derived from the necked section with any greater number of other sections.*

4. **Elasticity.** — When the initial part of the s.-d. diagram is a straight line, it is an indication that the material is practically perfectly elastic for the corresponding range. Thus in diagram II, Fig. 17, if the material is perfectly elastic for the range corresponding to AB, it could be stressed within these limits an indefinite number

* The value of ϵ for the point E in diagram I is derived from the **permanent elongation** after rupture; whereas for all previous points of the diagram the elastic elongation is included with the permanent elongation for the computation. The error due to this, however, is small enough to be negligible.

of times and each time it would return to its original dimensions. But in an s.-d. diagram like *ACB*, Fig. 18 — which is a record of a test of cast iron — there is no elastic

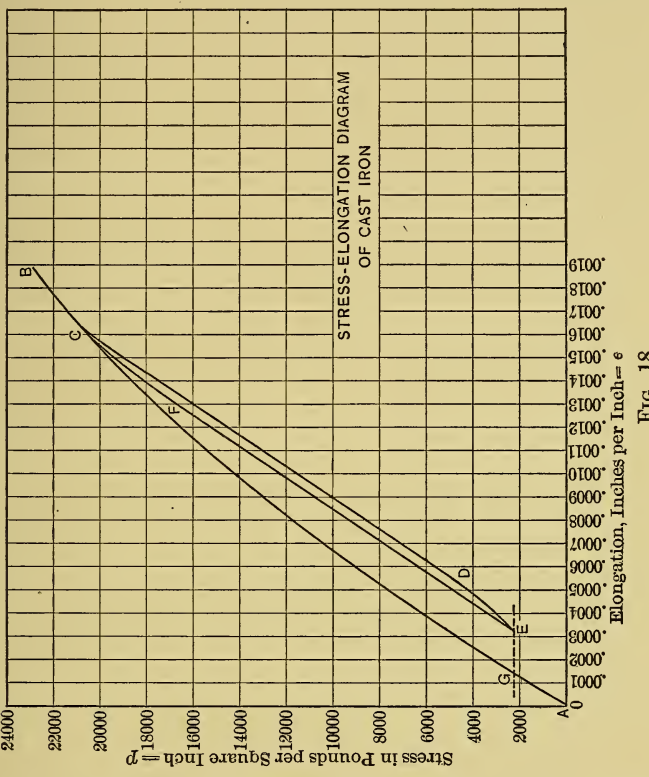


FIG. 18.

range and even small stress produces set. In this test stress was relieved at *C* and the diagram line traced the path *CDE*, showing a set at *E* * proportional to *EG*. Then

* Stress was not reduced to zero because of difficulties that would result in manipulation of the apparatus for measuring elongation.

stress was again increased until rupture occurred and the diagram line followed the path *EFCB*. It is evident that upon relief and reapplication of stress the line is not straight from *C* to *E* and again from *E* to *C*. The disappearance of elastic deformation occurs at practically a uniform rate from *C* to *D* — or *CD* is a straight line — and from some point *D* the rate of disappearance of elastic deformation increases to *E*; that is, *DE* is curved. The line of reapplication of stress *EFC* similarly is straight from *E* to some point *F*, while *FC* is a curve ending at the starting point *C*.*

It is obvious that the first application of stress has produced an **artificial elastic limit** *F*, together with a corresponding **elastic range** *EF*, and the stressed material may be considered as artificially elastic through this range.

The width of the loop *CDEFC* is only slightly affected by the **time** occupied in changing stress from *C* to *E* and back again to *C*; and hence the loop phenomenon must be a function of some quality of the material. Very careful measurements lead to the conclusion that the same phenomenon occurs with ductile material, but the **corresponding** values are too small to be detected by the measuring instruments of ordinary testing practice of engineering.

5. **Stiffness** of a material is a function of the amount of yielding under given force. It is measured by the ratio within the elastic limit of unit stress to relative elongation $= \frac{p}{\epsilon}$, and this ratio is called the **modulus of elas-**

* If relief of stress had been complete the curve *DE* would have continued to the *X* axis and would have returned at the left of *EF*, but a final curve would have brought the line to the same destination *C* as in starting from *E*. Thus the loop would be made wider.

ticity for tension, E_t.* Since for the material represented by Fig. 17 p is proportional to ϵ within the elastic limit, it follows that any corresponding values of p and ϵ between A and B — those at N, for example — may be taken to compute the value of E_t. The variation in stiffness has much narrower limits than tensile strength; thus, low-carbon open-hearth steel may have a tensile strength of about 60,000 pounds per square inch, while high-carbon crucible steel may have a tensile strength above 100,000 pounds per square inch, a variation of 100 per cent, probably; yet the values of E_t corresponding may be 28,000,000 and 32,000,000, a maximum increase of about 14 per cent. Practically all values of E_t for steel — of whatever grade — fall within the limits just given.

In the tension s.-d. diagram for cast iron, Fig. 18, ABC, the stress-deformation line is curved continuously from start to rupture, and hence the value of $E_t = \frac{p}{\epsilon}$ varies continuously and the original material cannot be said to have a definite modulus of elasticity. But since the material by relief and reapplication of stress from some point — as for example, C — is given an artificial elastic range, it follows that the stressed material would have an artificial value of E_t, measuring stiffness, corresponding to $\frac{p}{\epsilon}$ for any point in the straight line EF. This value of **artificial modulus of elasticity,** E_t, for cast iron probably averages about 15,000,000 pounds per square inch.

* The modulus of elasticity E_t is qualitatively the same as unit stress p; that is, it is a value expressed in pounds per square inch; for, $E_t = \frac{p}{\epsilon} = p \cdot \frac{l}{\lambda}$ in which $\frac{l}{\lambda}$, being a ratio of linear dimensions, is an abstract quantity; hence E_t equal to pounds per square inch multiplied by an abstract number must also equal some value expressed in the same units as p.

Resilience is the name given to the **work done** within a material while its form is changed by external forces. It is therefore the summation of the product of all stresses produced, multiplied by their yielding. But this summation is equal to the **work done by external forces in producing change of form;** hence this work is a measure of resilience.

In s.-d. diagram II, Fig. 17, work is done by the unit force which is initially zero and which increases uniformly to the elastic limit. Let unit force at the elastic limit be represented by p_1; then the average unit force up to the elastic limit equals $\frac{p_1}{2}$. This unit force acting upon one square inch section area has caused an elongation equal to ϵ in each one-inch section of length of the test piece, and hence $\frac{p_1}{2}\epsilon$ equals **the work done on one cubic inch of the test piece in bringing it to the elastic limit.** This value is sometimes called the modulus of resilience of the material and is represented by U_t.

The total **elastic resilience,** equal to the work done on the tested portion of the test piece up to the elastic limit, is equal to the total force $P = \frac{p_1}{2}F$, multiplied by the total elongation $= \lambda = \epsilon l$ or is equal to $P\lambda = \frac{p_1}{2}\epsilon Fl$. This value is proportional to the area of the triangle AB_1G and is equal to the modulus of resilience multiplied by Fl, the volume of the tested portion of the test piece.

The **ultimate resilience** is the work done in breaking the test piece. Consider s.-d. diagram I, Fig. 17. The mean height of the diagram Y_m measures the mean unit force acting throughout the test; while AE_1 — the final value of ϵ — measures the average elongation of each one-inch section of the tested piece. Hence the product

of Y_m and AE_1 — both expressed in inches — gives an area in square inches that is proportional to the ultimate resilience per cubic inch of the material. This value is obviously equal to the area of the diagram. Numerically this value in inch pounds per cubic inch equals the average value of p in pounds per square inch, multiplied by the final value of ϵ in inches per inch of test piece.

A machine member may be subjected to shock in use and it is necessary to know the shock-resisting capacity of materials of machines.

If a tensile shock were delivered to the piece whose test is recorded in Fig. 17, and if the energy of the shock were equal to the energy represented by the area AB_1G, it follows that the shock would stress the piece to its elastic limit. Hence the area AB_1G is proportional to the shock-resisting capacity of the material at the elastic limit. If s.-d. diagrams of different materials were plotted on the same scales, areas of triangles under the elastic limit could be compared to determine relative moduli of resilience or elastic shock-resisting capacity.

Similarly, areas under the complete s.-d. diagrams measure the capacity of the materials to resist rupture by shock, and comparison of these areas — in diagrams on the same scales — gives relative ultimate shock-resisting capacities.

In Fig. 19 diagram I is a reproduction on an enlarged scale of the initial part of the s.-d. diagram of mild steel given in Fig. 17. Diagram II, Fig. 19, is the s.-d. diagram of stressed cast iron like that represented in Fig. 18. The elastic limit of the mild steel is at B, while the artificial elastic limit of the cast iron is at B_1. The modulus of resilience of the steel is proportional to the area ABC, while that of the cast iron is proportional to the area AB_1C_1. Obviously the steel has greater elastic resilience than the stressed cast iron.

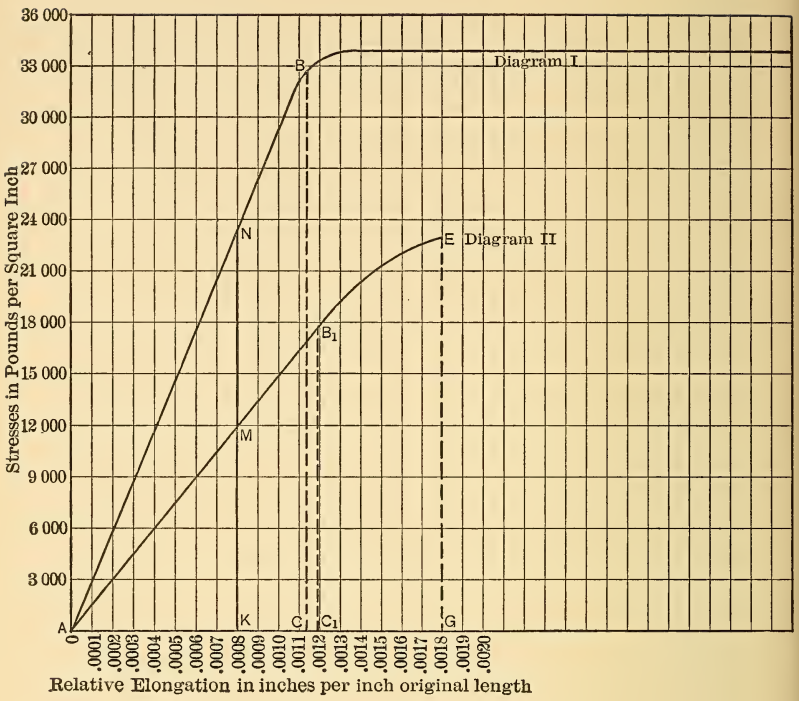


Fig. 19.

All of the elastic properties of mild steel and stressed cast iron can now be compared by reference to Fig. 19.

$$\frac{\text{Strength at elastic limit of mild steel}}{\text{Strength at elastic limit of stressed cast iron}} = \frac{BC}{B_1C_1} = 1.86$$

for this case.

Since **stiffness** is proportional to $\frac{p}{\epsilon}$ within the elastic limit, and since this ratio is constant within the elastic

limit, it follows that any value of ϵ less than AC may be chosen for the comparison; as for example, AK.

$$\text{Then} \quad \frac{\text{Stiffness of mild steel}}{\text{Stiffness of stressed cast iron}} = \frac{\frac{KN}{AK}}{\frac{KM}{AK}} = \frac{KN}{KM} = 1.95$$

for this case.

The relative elongation at elastic limit is measured by the ratio $\frac{AC}{AC_1}$.

$$\frac{\text{Modulus of resilience of mild steel}}{\text{Modulus of resilience of stressed cast iron}} = \frac{\text{area } ABC}{\text{area } AB_1C_1} = 1.8$$

for this case. This measures the comparative shock-resisting capacity at the elastic limit of the two materials tested.

The ultimate resilience of the stressed cast iron is proportional to the area AEG; while the ultimate resilience of the steel is proportional to the total area under the steel diagram which extends far beyond the limits of Fig. 19 (see diagram I, Fig. 17).

Compression. — In s.-d. diagrams of compressive tests unit stress is plotted downward and relative deformation is plotted toward the left. Fig. 20 shows diagrams of mild and high-carbon steel and of cast iron both in tension and in compression. Even if the strength of a given ductile material were the same in tension and compression, the compression diagram would have greater values of unit stress for the following reason:

In a tension test, elongation is accompanied by reduc-

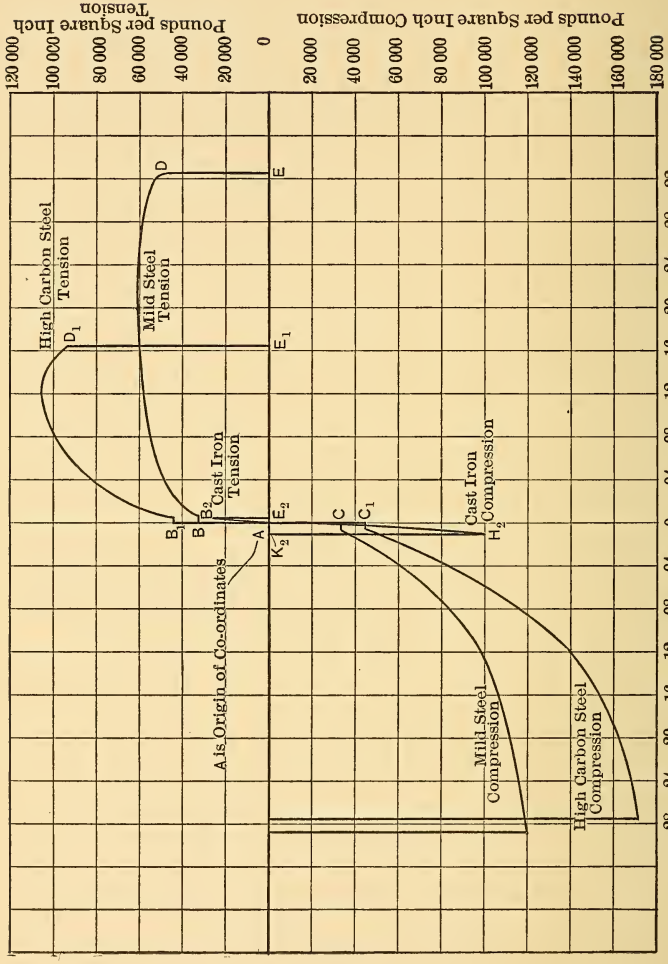

Pounds per Square Inch Tension
120 000
100 000
80 000
60 000
40 000
20 000
0
Pounds per Square Inch Compression
20 000
40 000
60 000
80 000
100 000
120 000
140 000
160 000
180 000
High Carbon Steel Tension
Mild Steel Tension
Cast Iron Tension
A is Origin of Co-ordinates
Mild Steel Compression
High Carbon Steel Compression
Cast Iron Compression
Relative Compression Inches per Inch
.28 .24 .20 .16 .12 .08 .04 .0 .04 .08 .12 .16 .20 .24 .28 .32
Relative Elongation Inches per Inch

FIG. 20.

tion of section area, since the density remains unchanged. The true unit stress at any point of the test would be total tensile force divided by the corresponding section area; but it has been decided for engineering tests to use the original section area as a divisor throughout the test and hence all values of unit stress in tension are really **too small.** On the other hand, in a compression test the section area **increases** with reduction in length and hence all values of unit stress in compression figured on the original section area are really **too large.** In the comparison of tension tests with each other this would not lead to error, nor would it lead to error in case of comparison of compression tests with each other; comparisons of tension with compression tests are probably unnecessary. This discrepancy in the s.-d. diagrams is of no importance within the elastic limit, since the change in section area up to that limit is negligible.

A ductile material like mild steel fails under compressive force either by splitting parallel to its axis, or by flattening out with a continually increasing section area, hence it is impossible to locate a definite breaking point.

A brittle material fails in compression by shearing on planes at about 45 degrees to the axis of the test piece.

S.-d. diagrams may also be plotted from the data of tests in which the external forces produce torsional or transverse stress as well as from the data of tensile and compressive tests.

CHAPTER VII

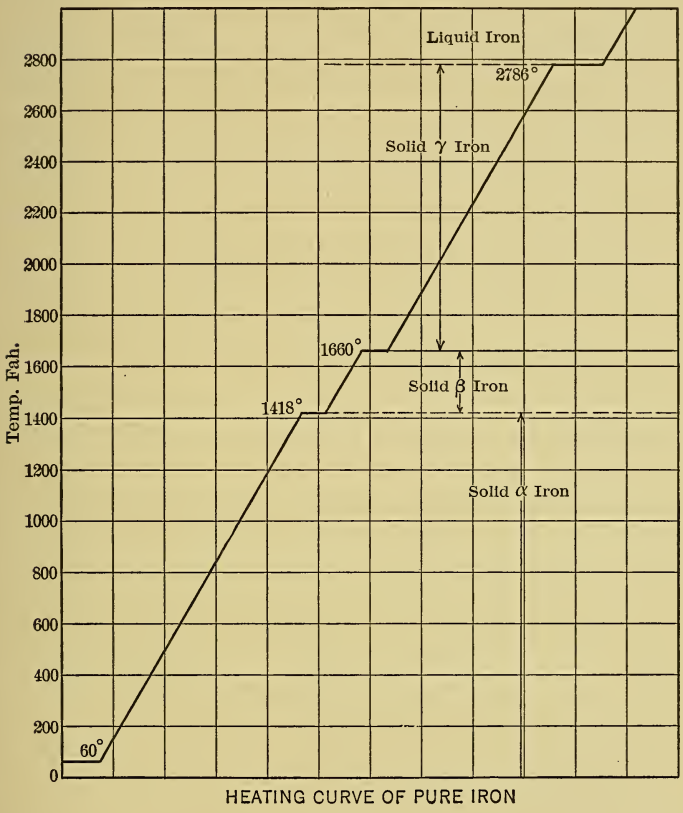
THE EQUILIBRIUM DIAGRAM OF IRON AND CARBON

Certain pure chemical elements occur in two or more so-called allotropic forms whose physical properties are quite different. Thus, diamond, graphite and charcoal are allotropic forms of carbon; oxygen occurs in two allotropic forms, O_2 and O_3 (ozone). In general, change from one allotropic form to another is accompanied by absorption or release of energy. The change may be due to rearrangement of molecules or of atoms, or to some other unexplained cause.

Iron has three allotropic forms called alpha (α) iron, beta (β) iron and gamma (γ) iron. Each form is stable — that is, it resists change into the other forms — within certain temperature limits. This is shown in Fig. 21. Temperature values in degrees Fahrenheit are laid off vertically upward. Horizontal spaces represent conventionally the time of heating or cooling. Between any attainable lower temperature and 1418° F. iron takes the form of solid α iron; at 1418° F. it changes to solid β iron and holds this form until 1660° F. is reached, where it changes to solid γ iron which melts at 2786° F.

The diagram represents heating, but the changes begin at the same temperatures whether the temperature change is upward or downward; whether the iron is heated or cooled. Alpha iron is soft and ductile with tensile unit strength of about 40,000 pounds at air temperature. It

is very magnetic, but loses this property entirely on changing into β iron. The crystal structure of α iron is like that of β iron, but is quite different from that of γ iron. A



HEATING CURVE OF PURE IRON

FIG. 21.

certain small amount of heat becomes latent during the change of α to β iron, and a larger amount becomes latent during the β to γ change. These and other facts show

that α, β and γ iron are allotropic forms with distinct physical differences.

Liquid iron will take freely into liquid solution many metallic elements, such as manganese, nickel, cobalt, chromium, tungsten, vanadium and copper, as well as non-metallic elements, such as silicon, carbon, phosphorus and nitrogen; certain quantities of these remain in **solid** solution when the iron solidifies in the γ form. When the cooling progresses into the β-iron field, though the metallic elements are probably held in solid solution, the non-metallic elements seem not to be retained. With further cooling into the α-iron field, moderate amounts of the metallic elements are held in solid solution, while the non-metallic elements are held only slightly or not at all.

Carbon is the most important element whose presence exerts a modifying influence upon iron. It may be associated with solid iron in solution, in chemical combination or in mechanical mixture. The phenomena accompanying changes of temperature of associated iron and carbon can be best explained by use of the so-called **equilibrium diagram.** Such a diagram is given in Fig. 22; it is drawn only with approximate accuracy. Temperatures are laid off vertically upward on the axis of Y, and percentages of carbon present with the iron are laid off horizontally toward the right on the axis of X. At A is the solidification temperature of pure iron and solidification becomes complete at this temperature; but as carbon is added to the iron the solidification begins at lower temperatures, as shown by the line AD. Moreover, while pure iron becomes completely solid at the temperature A, associated iron and carbon begin to solidify at temperatures defined by AD, but solidification does not become **complete** until some lower temperature, defined by AB, is reached. For illustration, the point h represents liquid iron contain-

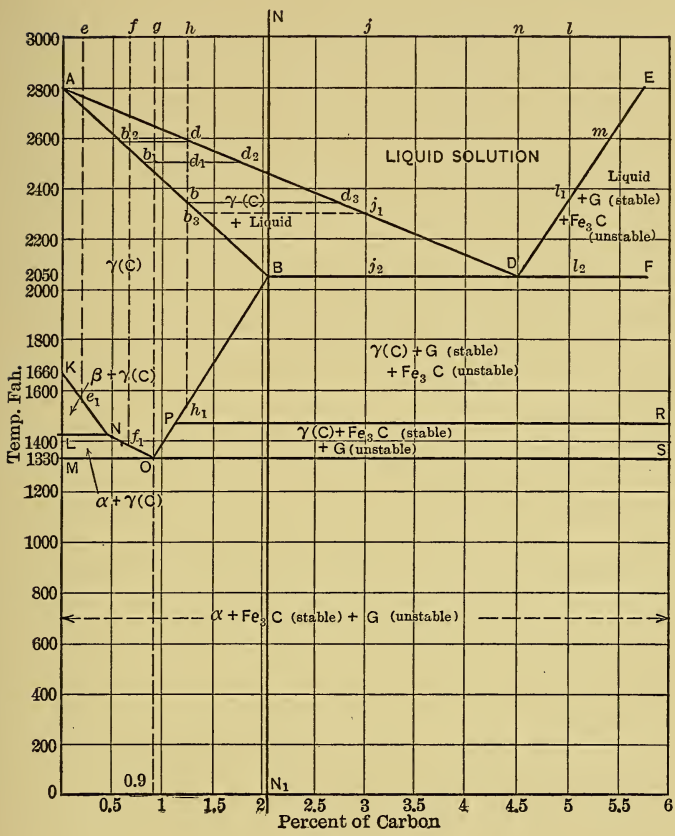


FIG. 22.

ing about $1\frac{1}{4}$ per cent of carbon at a temperature of 3000° F. During cooling the point moves from *h* vertically downward, and when it reaches *d* on the line *AD* solidification begins, but is not completed until the point moving vertically — with falling temperature — reaches *b* on the line *AB*.

The first crystals that form do not contain the proportions corresponding to d, but a smaller amount of carbon; in fact the composition is indicated by the point b_2, where a horizontal through d cuts AB. As d descends, the composition of the forming crystals is continuously indicated by the intersection with AB of the horizontal through the moving point; thus with the point at d_1 the composition of the forming crystals is indicated by b_1; at the same time the composition of the residual liquid, which grows constantly richer in carbon, is indicated by d_2 where the horizontal cuts AD. Thus crystals form continuously with increasing carbon content and this results in formation of crystal groups with cores low in carbon surrounded by layers of crystals having increasing carbon content.

Now, since the first-formed crystals have low carbon and since the **average** carbon content cannot change, it follows that the later-formed crystals must be high in carbon, and hence the outermost layers of the crystal groups must have carbon content much above the average value, and hence the point b_2 on AB, instead of stopping at b, continues toward B to some point that holds the average at b.

Obviously the solid cannot be homogeneous unless it is made so during or after solidification by redistribution of carbon by **diffusion.** Diffusion through the solid is a slow process and hence cooling must be very slow throughout the solidification range and afterwards if a homogeneous solid is to result.

In case of steel ingots, which are "stripped" and transferred to "soaking-pits" for slow cooling and heat equalization while the ingot interior is still liquid, undoubtedly there is time for diffusion of carbon to produce uniform distribution. But in steel castings the cooling is too quick to permit this result and there is,

as micro-photographs show, a lack of uniformity of carbon content in the crystals.

While the point is above AD the liquid iron holds the $1\frac{1}{4}$ per cent carbon in liquid solution; between AD and AB the carbon is partly in liquid and partly in solid solution, and below AB the mass is solid, the carbon being in solid solution in the iron. The results of cooling will be similar for any amount of carbon up to about 2.1 per cent, or with the cooling point located anywhere above AD and at the left of NN_1. Iron will hold carbon in liquid solution in amount according to temperature, as shown by the limiting line DE. Thus at 2600° F. iron will hold 5.4 per cent carbon corresponding to the point M; at 2800° F. the liquid solution is saturated with 5.75 per cent carbon; see point E. But 2.1 per cent seems to be about the limit of carbon in **solid solution** in iron. Therefore, if the molten mass contains more than 2.1 per cent carbon the excess must separate on solidification. This may be illustrated on the diagram. The point j represents 3 per cent carbon in liquid solution in 97 per cent iron at 3000° F. As this liquid cools the point moves vertically downward and when j_1, on AD, is reached, solidification begins; but the solid crystals first formed can only contain the amount indicated by b_3, about 1.3 per cent carbon, and hence it must have given up the residue of its original 3 per cent which is added to the residual liquid whereby that liquid is enriched in carbon. Thus the cooling point representing the composition of the **residual liquid** moves toward the right; in fact it moves along the line AD. Meanwhile the point representing the composition of the crystals moves along the line AB from b_3 toward B and the residual liquid grows richer in carbon until the cooling point that started from j_1 reaches j_2; the residual liquid composition corresponds to D and the mass solidi-

fies without further drop in temperature. The product of this final solution is γ (C), associated with **whatever is crowded out** during the entire change from liquid to solid. Since, by assumption, the other substance present is carbon, it follows that only carbon or compounds of carbon and iron could be associated with the γ (C). The solidified mass really does consist of intimately associated crystals of γ (C), carbon as graphite, G, and iron carbide, Fe_3C.

But the starting point of cooling might have been at some point at the right of nD, for example, l, representing a liquid solution of 5 per cent carbon in iron. The point l, moving vertically downward during cooling, reaches the line DE where the liquid iron is **saturated** with carbon and where further fall in temperature results in separation of solid crystals, probably Fe_3C *, which may change in part to graphite in the effort to establish equilibrium. The remaining liquid is thus impoverished in carbon and hence the point representing composition of residual liquid moves toward the left; in fact it follows the line ED to D, and during this progress Fe_3C separates continuously. At D the **residual liquid** contains 4.5 per cent carbon in liquid solution, and during final solidification at constant temperature the excess of carbon over 2.1 per cent is crowded out as Fe_3C and graphite. The product of solidification at D from initial condition j and at l are similar, but of course with different proportions of γ (C) and G + Fe_3C.

With n as the starting point of cooling the liquid consists of a 4.5 per cent solution of carbon in iron and the cooling line cuts AD and ED at their intersection D.

* It seems to be accepted as a fact that when two forms may separate from a solution the form that is unstable under the conditions separates first.

Hence no preliminary separation of γ (C) occurs as with the line of cooling at the left of nD, nor preliminary separation of Fe_3C and graphite as with the line of cooling at the right of nD, but the solution remains constant until D is reached, and solidification begins and ends at that temperature. Before solidification the mass is all liquid solution with 4.5 per cent carbon; after solidification the iron holds 2.1 per cent carbon in solid solution, but the excess of carbon above 2.1 per cent separates as cementite (unstable) or graphite (stable). Hence the solid product of cooling from n consists of intimately mixed crystals of γ (C), Fe_3C and G with the total carbon present equal to 4.5 per cent. This solid is called "eutectic," and D is the "eutectic point."

With cooling from j the solid product consists of eutectic formed at D mixed with excess of γ (C) with varying carbon content formed during temperature change from j_1 to j_2. With cooling from l the solid product consists of eutectic formed at D mixed with excess of G and Fe_3C formed during temperature change from l_1 to l_2.

Certain changes in composition of associated iron and carbon also occur as temperature falls after complete solidification.

The lines KNO, BO, LN and MO (Fig. 22) have been located on the diagram by careful experiments. At K is the temperature of interchange between the β and γ forms of pure iron. The sloping line KN indicates the drop in temperature of β, γ interchange due to increasing proportion of carbon. At L is 1420° F., the temperature of interchange between α and β forms of pure iron, and between L and N any free iron in the mass would interchange between β and α at the constant temperature LN. The sloping line NO indicates the drop in temperature of α, γ interchange due to increasing proportion of carbon.

The line *BO* defines the lowest temperatures at which γ (C) solid solutions can exist without separation of cementite or graphite, or it is the line of solid saturation.

First illustration.— The point *e* represents a solution of 0.2 per cent carbon in liquid iron at 3000° F. As this point moves vertically downward on the line ee_1 during slow cooling, it passes the line *AD* where solidification begins, and the line *AB* where solidification ends. The point continues to move vertically downward, the cooling material remaining γ (C) and with slow cooling probably becoming homogeneous by diffusion, until the line *KN* is reached at e_1; at this point some of the iron changes from the γ (C) to the β form, and since β iron cannot hold carbon in solution, the γ (C) that is thus left is impoverished in iron; hence the cooling point moves in the direction of increased carbon toward the right; in fact it moves along the line *KN* until the point *N* is reached; at this temperature, 1420° F., the β iron that has separated out as **pure** iron changes — as any pure iron would at that temperature — into the α form, while more iron separates from the γ (C) as α iron, causing further iron impoverishment of the remaining γ (C); then the cooling point moves along the new slope, *NO*, until the point *O* is reached at the lowest temperature at which iron can exist in the γ form, and the **residue of γ (C) changes into a eutectic mixture called pearlite, consisting of α iron and Fe_3C.**

Second illustration. — Let *f* be the starting point of cooling with 0.7 per cent carbon. As before, the cooling point passes the lines *AD* and *AB*, where solidification of γ (C) is completed, and arrives at f_1 on the line *NO*, where γ iron changes into α iron (possibly passing through the intermediate β form) impoverishing the remaining γ (C) in iron and causing the point to move along the line *NO*

to the point O where the eutectic pearlite is formed as in the first illustration.

Third illustration. — With g as the starting point of cooling the carbon equals 0.9 per cent, which is just the proportion corresponding to the eutectic; the point goes vertically downward passing AD and AB, the range of solidification, and continuing to O where, since this is the eutectic point, the γ (C) changes directly into the eutectic pearlite.

Fourth illustration. — With h as the starting point of cooling, the carbon equals 1.25 per cent and the point moves through the solidification range and finally reaches h_1 on the line BO. Here the condition is that of a solid saturated solution of carbon in iron and hence further reduction in temperature results in separation of Fe_3C. The result is that the remaining γ (C) is impoverished in carbon and hence the point must move to the left; it really does move along the line BO and finally reaches O, where the γ (C) changes into the eutectic pearlite as before.

If the cooling point starts at the left of g, iron separates from the γ (C) along the line KNO to leave the eutectic proportion at O, and the resulting mass consists of crystals of α iron intermixed with eutectic pearlite.

With g as the starting point of cooling all γ (C) changes directly into eutectic and hence the resulting mass will consist of the eutectic alone.

With the starting point of cooling at the right of g, Fe_3C separates from the γ (C) along the line BO to leave the eutectic proportion at O, and the resulting mass consists of eutectic pearlite with crystals of Fe_3C.

Upon the fields of the diagram, Fig. 22, are given the forms there taken by associated iron and carbon. Thus above the lines AD and DE there can be only liquid solution. To the right of DE (since the line DE gives the

saturation limit) carbon in excess of saturation must exist separately — usually as graphite — in fact in this field graphite separates by gravity and floats on the surface, thus carrying the residual mass back to the saturation line. Fe_3C is also present in this field since it separates first and since change into the more stable graphite occurs very slowly.

Cooling lines from the field *ADE* enter the field *FBPR* through the eutectic point *D*, carrying eutectic with amounts of graphite and cementite that vary according to the location of the starting point of the cooling curve.

The line *PR* has been carefully located where graphite, G, and cementite, Fe_3C, interchange stability. Above this line cementite tends to rapid change into graphite (giving up its combined iron), while below this line graphite tends to become cementite slowly, taking up the required iron. Below the line *MS* iron cannot exist in the γ form, but changes into the α form, carrying graphite (unstable) and cementite (stable).

CHAPTER VIII

CAST IRON

The blast-furnace produces different grades of pig iron that are usually numbered from 1 to 6, although the numbering scheme varies in different countries and in different localities in the same country. When the product of the blast-furnace has been melted in a foundry cupola, or a reverberatory furnace, cast into sand molds and cooled, it is called **cast iron.**

Cast iron usually contains carbon, silicon, manganese, sulphur and phosphorus; its physical properties differ from those of pure iron because of the presence and interaction of these substances.

Carbon is usually present in cast iron in two forms: (*a*) as pure carbon in the form of distributed crystals of graphite, and (*b*) as combined carbon in the form of distributed crystals of cementite, Fe_3C. These forms are usually called **graphite** and **combined carbon.**

Cementite is an intensely hard and very brittle substance, and the influence upon iron of a very small proportion of carbon in this form is very great. This is partly due to the fact that a small weight of carbon makes a large weight of Fe_3C. Taking the atomic weight of carbon as 12 and of iron as 56 the ratio of weight of cementite to the contained carbon equals $\frac{(56 \times 3) + 12}{12} = 15$; hence iron that has one per cent by weight of combined carbon may really have 15 per cent by weight of Fe_3C. Since

the specific gravity of iron is 7.8 and of Fe_3C is 7.07, it follows that the **volume** of Fe_3C in the case just cited is 16.3 per cent.

Percentages by weight and by volume of Fe_3C in iron with varying carbon may be tabulated as follows:

Per cent weight carbon	Per cent weight Fe_3C	Per cent volume Fe_3C
1	15	16.3
2	30	32.1
3	45	47.4
4	60	62.3
4.5	67.5	69.6

These values result from the assumption that only iron and carbon are present and they would of course be modified in the case of actual cast iron; but they show how great an influence a small amount of combined carbon may have on cast iron.

Since cementite is hard and brittle, its presence in large proportion gives similar qualities to cast iron. In fact, **white cast iron,** in which carbon is chiefly in the combined state, is weak in tension, though strong in compression; it is so hard that it can only be machined by grinding; it is also brittle, that is, it has very low ductility and resilience; but it has great resistance to wear and hence it is produced by "chilling" in the surfaces of rolls for rolling steel and in the treads of cast-iron car wheels.

Graphite is an allotropic form of carbon and when it is present in cast iron it produces a gray fracture and interrupts the continuity of the iron structure and thus reduces the strength of the iron with which it is associated.

Conversion of the carbon of the Fe_3C of white cast iron into the graphite of gray cast iron leaves the iron of the Fe_3C (which may be a large proportion of the mass) in

the α form and thus substitutes a ductile material strong in tension for a brittle one; moreover, both the iron and graphite are soft and hence the change from white iron to gray iron, except in extreme cases, is accompanied by increased tensile strength and ductility and softness; the compressive strength is decreased. **Hence means for control of carbon between the states of cementite and graphite are of great importance.**

The total carbon in cast iron is almost always within the limits 2.6 per cent and 4.6 per cent; therefore, in Fig. 23, the lines QQ_1 and HH_1 bound the cast-iron field on the equilibrium diagram.

Molten iron associated only with carbon, ready for casting, would be represented by some point in the field above qDr at (say) 2400° F. If, during melting in contact with carbon fuel, the iron had become saturated with carbon — as often occurs — the cooling point would be at w and during cooling either in the ladle or mold, Fe_3C would separate and with sufficient time the carbon would change to graphite which would float as long as the mass remained fluid enough for gravity to cause the separation, and afterward would be irregularly distributed throughout the mass. Thus the cooling point would follow wD to D where the eutectic* would be formed, and this eutectic would be more or less uniformly mixed with the graphite that separated along wD through the Fe_3C form. Doubtless also some Fe_3C would remain unconverted.

As very slow cooling goes on the line PR is reached where the stability of G and Fe_3C interchange, and there is a tendency for the graphite formed to take up iron and

* λ (C) with 4.5 carbon in liquid solution changing into crystals of λ (C) with 2.1 per cent carbon in solid solution, intimately associated with crystals of graphite corresponding to the residue of the 4.5 per cent carbon.

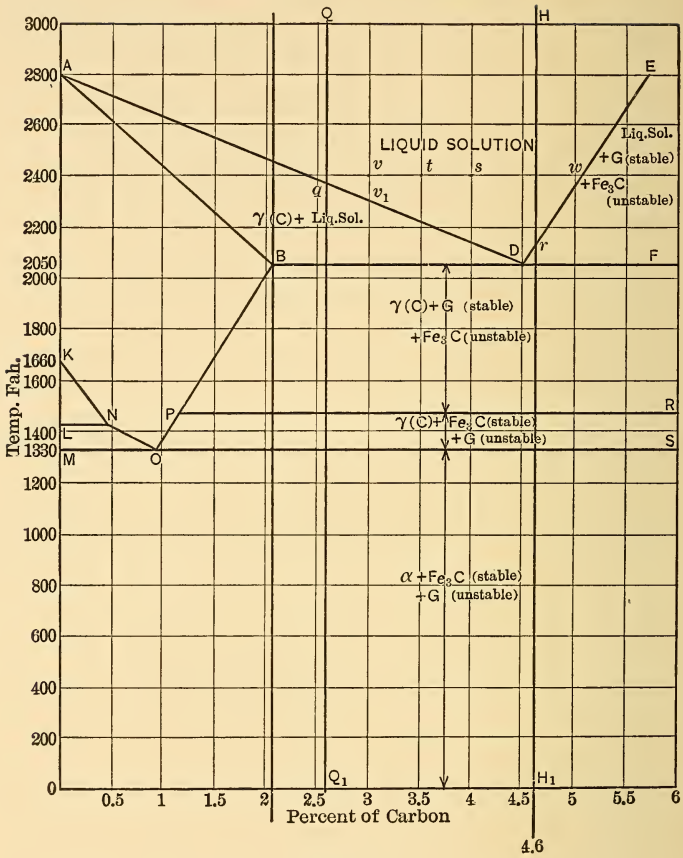


FIG. 23.

to become Fe_3C. This tendency, however, is less if a large amount of graphite is present and especially if it is present in large flakes. At the line *MS*, since this represents the lowest temperature at which γ iron is stable, γ (C), with slow cooling, tends to change into α iron and Fe_3C; but here also the presence of graphite, especially in large

flakes, tends to oppose the change and may compel the decomposition of γ (C) into α iron and temper graphite.* In this case the resulting mass will have with the α iron a large amount of graphite as flakes and temper graphite and a relatively small amount of cementite. It would therefore be a gray iron.

But suppose that the cooling point instead of starting from w should start from some point v corresponding to 3 per cent of carbon and 2400° F. The point would descend vertically to v_1 and follow v_1D with separation of solid γ (C), which would be more or less uniformly distributed throughout the mass; on reaching D the residual liquid would be decomposed into the eutectic (as before intimately associated γ (C) and G). The resulting mass, therefore, would consist of eutectic with excess of γ (C), and with very slow cooling, in the absence of excess of large flake graphite, on reaching PR the graphite wholly or in part would take up iron and become Fe_3C. Hence between PR and MS the mass consists of γ (C) + Fe_3C + some graphite. At MS the γ (C) is decomposed (in the absence of large flake graphite) into α iron and Fe_3C. This mass would have large excess of Fe_3C and little graphite and hence would be a white or light gray iron.

Chilling. — The changes just considered are accomplished slowly and hence rapid cooling might render them incomplete, while sudden cooling might suppress them entirely. If molten cast iron were poured into an ample bath of cold water, cooling would be sudden and the cooled iron would have a large proportion of its carbon in solution, γ (C), because of lack of time for the change, while a small proportion would be combined in Fe_3C. Between this extreme of sudden cooling and the other extreme of

* Temper graphite is graphite very finely divided; in fact, it is a microscopic dust, uniformly distributed as in malleableized castings.

very slow cooling, the cooling rate can be varied with the production of intermediate results.

In casting chilled car wheels, the portion of the mold that forms the tread is of iron, which conducts heat away rapidly, while the portion that forms the rest of the wheel is of sand, which conducts heat away slowly. Thus the tread is "chilled" and, with proper grade of iron, cools white, while the rest of the wheel is gray, with an intermediate territory of mottled iron. This gives a wheel with a very hard tread to resist wear, a strong web and a hub that is not only strong but soft for machining. See Fig. 24.

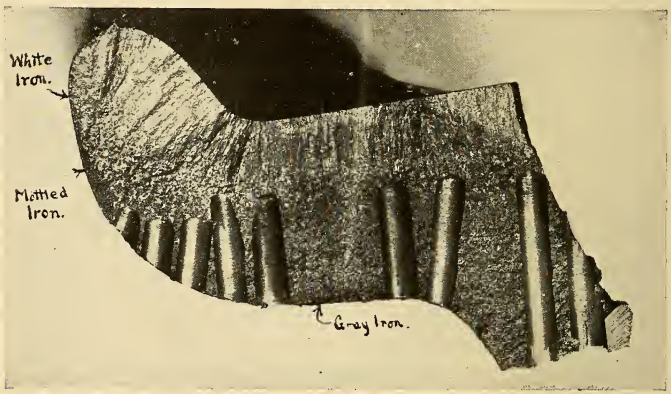


FIG. 24.

The rate of cooling of castings made in sand molds varies. The rate of outflow of heat is proportional to the **external surface** of the casting, while the heat to be removed to effect cooling is proportional to the **volume** of the casting; hence the rate of cooling depends upon the ratio of **surface** to **volume** of the casting, and it follows that thick castings cool more slowly than thin castings.

Hence the same iron cast into thick and thin forms would give castings of different composition, structure and properties.

If it is desired to accelerate cooling, the sand of the mold which acts as heat insulation may be removed as soon as the iron is cool enough to hold its form.

The form of carbon in cast iron may be **controlled** by regulation of the quantities of other substances present.

Manganese is held in solid solution by iron in a wide range of proportions; it also may combine chemically with carbon to form a carbide, Mn_3C, which goes into solid solution with Fe_3C to form what may be called iron-manganese carbide. The carbide Mn_3C is hard and brittle and its association by solution with Fe_3C, which is only a little less hard and brittle, would presumably produce a compound with similar qualities, which it would give in less degree to the mass with which it might be associated. Moreover, since the manganese must take up carbon to produce the carbide it would reduce the carbon which, in its absence, would appear as graphite; thus gray iron would become whiter.

Authoritative tests seem to show that addition of manganese to mild steel increases tensile strength, and that ductility, though little changed up to 0.5 per cent, is reduced with further additions of manganese until at 2 per cent the steel is quite brittle. Since there is a very small amount of carbon in this mild steel, it is probable that these effects are due to manganese in solution with the iron itself.

Whatever the theory may be it is certain that manganese up to 1 per cent in cast iron increases strength and probably reduces ductility, and that in larger amounts it tends to change graphite into combined carbon.

If **sulphur** is present in cast iron its form is FeS, and

it has a very decided tendency to cause graphite to become combined carbon. This tendency of sulphur is much greater than that of an equal amount of manganese to produce the same result. When manganese is added to a cast iron containing sulphur it takes sulphur from the FeS to form MnS. Consider now three substances: (*a*) iron sulphide, (*b*) manganese sulphide, (*c*) iron manganese carbide. (*a*) has greatest power to convert graphite into combined carbon; (*c*) is next in order and (*b*) has least power to produce this result. With a given amount of FeS present the addition of manganese in amount that would just take all sulphur to form MnS, would convert a substance, FeS, with great power to make gray iron white into a substance, MnS, with small power for this result; and thus the graphite would **increase** at the expense of combined carbon and the iron would become grayer. Further increase in manganese would now produce an increasing amount of iron manganese carbide with increasing tendency to make the gray iron white, until finally this tendency would just equal that of the sulphur before any manganese was added and further increase would make the iron whiter still. Obviously, the limits of this reversed action depend on the amount of sulphur present. With no sulphur, the effect of increasing amount of manganese would be increasing tendency to whiten the iron; whereas when sulphur is present, the effect of increasing amount of manganese would be first to neutralize the sulphur with increasing grayness of the iron, and then to turn the gray iron whiter. This explains why a small addition of ferromanganese to molten sulphur-iron may act as a softener. Sulphur is undesirable in cast iron, causing hardness, weakness and brittleness; it should not exceed 0.15 per cent and thus it should not be used as a means for regulation of the state of carbon.

Manganese, on the other hand, within limits has a desirable effect upon strength and hence may be used to regulate carbon.

Silicon is held in solid solution by α iron up to about 2 per cent and up to this limit it seems to increase the strength and to reduce ductility of iron; beyond this limit Fe_2Si forms in increasing amount, and the presence of this silicide reduces strength, ductility and shock resistance of cast iron. Silicon also tends to reduce iron oxide, to remove gas that causes porosity and to increase the fluidity of the molten iron, so that stronger, denser and sharper castings are produced. **Silicon also tends to force carbon from the combined to the graphitic form, or to make iron grayer.** Possibly silicon that forms Fe_2Si takes the iron for this purpose from Fe_3C, thus leaving the carbon to take graphitic form. Obviously, silicon would tend to neutralize the effect of manganese and sulphur to make iron whiter.

Ferrosilicon, as high silicon pig iron is called, is now on the market, and its use in the foundry cupola charge gives control of the silicon in castings and thus within limits gives control of the state of the carbon in the cast iron.

To determine the effect of a varying proportion of silicon upon cast iron, Professor Thomas Turner made a series of experiments which were reported under the title "Influence of Silicon on the Properties of Cast Iron" in the *Journal of the Chemical Society* in 1885. He used iron with as nearly as possible 2 per cent carbon and with sulphur, phosphorus and manganese quite low, and by introducing ferrosilicon he was able to produce test pieces with desired proportions of silicon. These were tested and results in tensile and compressive strength and hardness are plotted in Fig. 25.

Progress from *O* toward the right, with increasing

tensile strength and decreasing hardness, probably corresponds to the combined effect of solution of silica in iron, and the influence of formation of Fe_2Si to increase graphite at the expense of combined carbon.

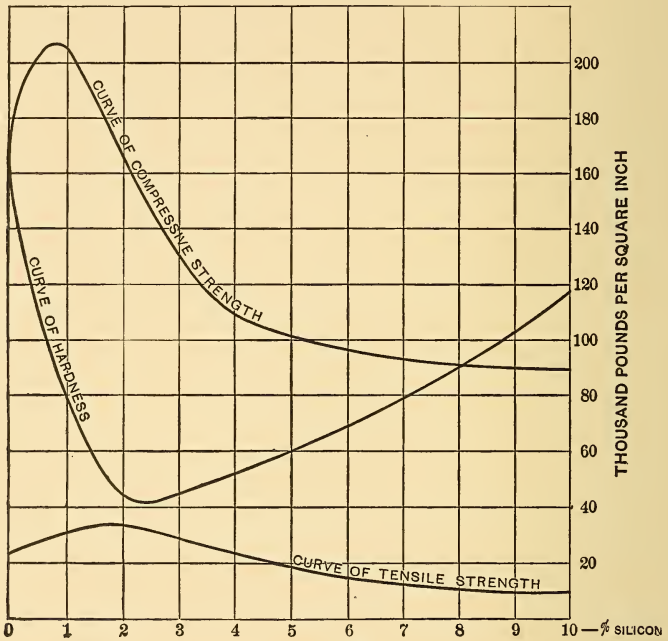


FIG. 25.

As has already been stated, white iron is stronger in compression than gray iron, and hence the compression curve should fall from the start whereas it rises up to about 0.8 per cent. This may be due to the direct action of the silicon upon the iron or to the fact that small amounts of silicon tend to reduce the porosity that is common in white cast iron and to give sounder and hence stronger castings.

It is clear from these tests that by varying the silicon content it is possible to control very materially the physical properties of cast iron. It would be very helpful to know what the effect of increasing silicon would be with the total carbon higher than 2 per cent to correspond more nearly to foundry practice.

Phosphorus probably goes into solid solution in iron in amounts such as are usually present in steel; but as it increases to the values common in cast iron a large part of it becomes Fe_3P. Phosphorus may affect cast iron in three ways: (*a*) directly, by solution in the iron; (*b*) indirectly, by its power to cause graphite to become combined carbon; (*c*) indirectly, because its presence causes cooling iron to pass through a pasty state thus delaying solidification. This delay makes it possible for tendencies that are active in the cooling mass to produce more complete results. Thus with high silicon the presence of phosphorus — by delaying solidification — might enable the silicon to produce a larger proportion of graphite, thus giving a softer iron stronger in tension in spite of the opposite effect of the phosphorus itself. Obviously the resultant effect would depend on the relative amounts of the silicon and phosphorus present and with low silicon and high phosphorus the effect would undoubtedly be to whiten the iron. (*a*) and (*b*) produce harmful increase in hardness and brittleness; (*c*) in the presence of silicon **may** produce a desirable increase in strength and softness. Again, whatever theory may be right, it is a fact that although phosphorus is a very detrimental constituent in steel, it is not harmful in cast iron, often being present up to 1.3 per cent. Phosphorus is useful in cast iron because it increases the fluidity of the molten mass so that sharp castings can be made with lower casting temperature.

Semi-steel. — There is another method of carbon control that gives excellent castings. In case of cast iron with low total carbon, if all or nearly all of the carbon could be caused to appear as very finely divided graphite — like temper graphite in malleableized castings — there would be very low cementite and relatively small interference with the continuity of the iron by the graphite, and hence the iron would be strong and soft.

In many foundries it is now customary to introduce with the regular cupola charge about 25 per cent of steel scrap, which mixes with the cast iron and melts. Neglecting the carbon of the steel, and assuming the total carbon of the rest of the charge to be 4 per cent it follows that the total carbon would be reduced by dilution to 3 per cent. Or in Fig. 23 the starting point of cooling would be moved from s to v. Cooling slowly from v with only carbon and iron present would give a white iron. Addition of sulphur, phosphorus and manganese in customary amounts would leave the iron still white; but addition of silicon in sufficient quantity could cause most of the carbon to appear as finely divided graphite (since the total carbon is low), giving a soft strong iron. It is interesting to note that there is a possible ideal relation of quantity of these substances; viz., with a certain necessary amount of sulphur there should be enough manganese to convert all of the FeS to MnS. The total carbon should be kept low enough by dilution so that when the greatest possible proportion is converted into graphite, it shall appear as very fine grains instead of as flakes. The amount of silicon should be sufficient to provide for the fluxing that removes iron oxide completely and prevents porosity, and also by solution or chemical combination to cause the maximum change of combined carbon into finely divided graphite. There should be just enough

phosphorus to delay solidification for the silicon to produce its best result without too great phosphorus effect on carbon and iron. It would probably be impossible to produce this ideal result, but it is true that the so-called semi-steel often has tensile strength above 30,000 pounds per square inch, together with close grain and good wearing resistance and softness for easy machining.

Aluminum introduced into molten cast iron produces two results. A part combines with oxygen to form alumina, thus reducing undesirable oxide of iron and absorbing gas that would cause porosity. The alumina thus formed combines with other waste and forms either a fusible slag or an infusible crust which is removed. Another part of the aluminum — if there is an excess — may combine with the iron, and when it does, as shown by Mr. J. W. Keep,* its influence upon the distribution of carbon is similar to that of silicon. But although ferro-aluminum is on the market, it is not used as a softener of cast iron because it is more expensive than ferrosilicon, which produces the same result; moreover, when aluminum is used, a skin that forms on the surface of the molten iron tends to cause "cold shuts" and defective casting surfaces.

Malleable cast iron. — Theory of mallifying process for production of malleable cast iron.

An average composition of castings for mallifying is as follows:

	Per cent
Total carbon	2.75
Silicon	0.8
Manganese	0.4
Phosphorus	0.17
Sulphur, under	0.05

* See *Transactions Am. Inst. Mining Engineers*, Vol. XVIII, p. 102.

These castings with low carbon, low silicon and relatively high manganese and phosphorus, and with the relatively quick cooling which corresponds to malleable iron foundry practice, hold all carbon in the combined state; that is, the casting fractures white. In the mallifying process the castings, packed in iron oxide or other material, are raised to a temperature of from 1500° to 1600° F. This brings them into the lower portion of the field (Fig. 23) bounded by the lines QQ_1, HH_1 and BF, PR, where graphite is stable and where Fe_3C is unstable. In passing the line OS upward the α iron changes into γ iron and takes carbon into solution to form γ (C); but the amount of carbon available is small, since Fe_3C is stable in this field, and hence probably γ (C) holds less than 1 per cent of carbon in solution. The castings are held in the field above PR for about 60 hours, and this time is sufficient for the stability tendencies to reach equilibrium, and most of the Fe_3C gives up its carbon to form temper graphite which appears as uniformly distributed microscopic dust.* The iron thus isolated in this field by decomposition of Fe_3C is in the γ form, and it takes silicon and carbon into solution, forming γ (Si, C). If no silicon were present γ (C) would be formed, but when silicon is present it crowds out and replaces a part of the carbon of γ (C) giving γ (Si, C). Hence the greater the amount of silicon within limits the greater the amount of carbon that appears as temper graphite. The result, therefore, of holding the castings in this field is production of γ (Si, C) with low carbon, associated with temper graphite and, undoubtedly, with a small amount of unchanged Fe_3C.

* Probably the carbon takes this form here because the mass is resistant to the migration of the carbon. When the eutectic is formed at D, the solidifying mass, being less resistant, permits the separating graphite to migrate through the mass and to unite into graphite flakes.

When the slow cooling takes place, on passing *OS* the γ iron of the γ (Si, C) changes back to α iron, releasing the carbon but holding the silicon in solid solution, α (Si).* The released carbon in the presence of the α (Si) and of the temper graphite already formed is forced, in opposition to the equilibrium tendency of this field, to become temper graphite, and thus the mallifying process is complete and the cooled castings are strong and ductile with a fracture that is black with temper graphite with a thin white skin. The reasoning given applies only to the interior portion of the castings, since the white skin that is formed on the castings during mallifying has its total carbon notably reduced by oxidation either by the oxygen of the air trapped in the packing, or by the oxygen of the oxide packing itself, thus becoming a skin of something like mild steel. The ductility of this skin is of great importance in the malleable castings, and its removal sensibly diminishes their value as stress members of machines; hence the stress-parts of malleable castings are seldom machined.

The "white heart" malleable castings of England and the continent of Europe consist of light or very thin castings that are almost completely decarbonized, like the skin of the American "black heart" castings, by higher mallifying temperature and extension of the time of mallifying.

Shrinkage. — When molten cast iron is poured into a mold it takes the form of the mold and cools gradually to the temperature of the surrounding air. Shrinkage which accompanies cooling may be divided into **fluid** shrinkage and **solid** shrinkage.

As the molten iron in the mold after casting begins to cool, it shrinks in volume. This shrinkage may be "fed

* Some silicon is also in solid solution with the remaining Fe_3C.

from a riser," * until the connection is frozen up. The walls of the casting solidify, but at first are weak and yield to the shrinkage of the still fluid iron within the casting; if the volume of the casting is large, depressions in the walls result. Later the walls become rigid enough to resist shrinkage of the remaining fluid within, and since the volume cannot be reduced further, portions of the mass pull apart and the casting becomes spongy. A spongy cross section is necessarily weaker than one of solid iron, and is therefore undesirable in a machine stress member. Evidently the tendency to form spongy iron because of unsupplied fluid shrinkage increases with the volume of the casting.

Experience points to the conclusion that castings of small cross section shrink more than those of large cross section. To test this conclusion, Mr. Thomas D. West made an experiment, which he describes in his book "American Foundry Practice." He cast two bars 14 feet long, from the same iron, and as far as possible made the conditions of casting the same for both. The cross sections were rectangular, one being 4 inches by 9 inches and the other $\frac{1}{2}$ inch by 2 inches. The total shrinkage for the larger bar was $\frac{7}{8}$ inch and for the smaller one was $1\frac{3}{4}$ inches. This may possibly be explained as follows, as Mr. West suggests: A casting cools from the surface, and therefore during the cooling the surface will be the coolest part, and the heat will increase toward the center. The external portions are held from their normal shrinkage

* A "riser" is formed by making a vertical cylindrical opening in the sand which connects with the main portion of the mold. The molten iron during pouring rises in this cylindrical opening to form the riser. If the riser is large in proportion to the casting it remains fluid for some time and acts as a reservoir to supply fluid shrinkage. Molten iron from a ladle may be fed in to maintain the level in the riser.

by the resistance of the hotter internal portions, which are not yet ready to shrink as much. This goes on until the surface has reached the temperature of the surrounding air and stops shrinking; the hotter portions nearer the center now try to shrink as they in turn cool down, but are prevented by the external part which has stopped shrinking, or it may be that since the thicker portion cools more slowly than the thinner portion, it will be grayer and the formation of graphite reduces the natural shrinkage of the iron. Whatever theory is correct, the fact remains that castings of small section shrink more than castings of large section. It follows that castings having thick and thin parts attached to each other will shrink unequally, and be in a state of internal stress, which renders them less able to withstand the action of external forces.

Suppose it is required to put a strengthening rib B on A, Fig. 26 (a), and that it is made of the form shown, i.e., thin relatively to A, and having parallel sides. B would shrink more than A, and shrinkage stresses (tension in B and compression in A) would result, which would be concentrated along the juncture of A and B, and yielding would occur under a less external force. If the form shown in (b) were used, where the rib tapers from the thickness of B to the thickness of A, the shrinkage stresses would be distributed, and the casting would be stronger.

The lessons to be learned from these facts are as follows: (1) All parts of all cross sections of castings for machine members should be as nearly of the same thickness as possible, to avoid concentrated shrinkage stresses, with their accompanying weakness. (2) If it is necessary to have thick and thin parts in the same casting, change of form from one to the other should be as gradual as possible. (3) Castings should be made as thin as is consistent with

strength, stiffness and resistance to vibration, to avoid the shrinkage stresses, and spongy metal due to the shrinkage of large masses. (4) Since some shrinkage stresses always must exist in cast machine members, they should be taken into account in designing.

Special care should be taken in the design of wheels, because they are peculiarly liable to excessive shrinkage stress on account of their form. In a pulley, the thin rim tends to shrink more than the heavier arms, and the rim is thereby put in tension, and the arms in compression. It is not uncommon to see a rim ruptured in this way. If the same pulley has a relatively heavy hub, the latter will remain fluid until the arms and rim have solidified; the tension on the rim will then force the arms into the yet fluid hub, which in turn shrinking, will put the arms in tension. The arms of fly-wheels tend to shrink away from the heavier rim, and are therefore in tension.

White iron shrinks more than gray iron, and the reason is obvious. When graphite is formed from the γ (C) or Fe_3C a substance of low density replaces a substance of high density and the volume of the mass is thereby increased.

TABLE OF DENSITIES OF DIFFERENT GRADES OF CAST IRON *

Grade of iron	Specific gravity
Pure iron	7.86
White cast iron	7.60
Mottled cast iron	7.35
Light gray cast iron	7.20
Dark gray cast iron	6.80

* Abridged from "The Metallurgy of Iron and Steel" by Bradley Stoughton (McGraw-Hill Book Co.).

The white castings for mallifying shrink more than gray castings; but during mallifying, as a result of the appear-

ance of low-density graphite, the castings expand. The resultant shrinkage due to the entire process for production of malleable cast iron is about the same as the shrinkage of gray castings.

Effect of internal stress upon the strength of castings. — Suppose that a casting is made of the cross-sectional form shown in Fig. 26 (a). The part *B* tends to shrink more than *A*, and, therefore, *B* is put in tension and *A* is put in compression. Where there is compressive stress, and tensile force is applied, the first effect is the

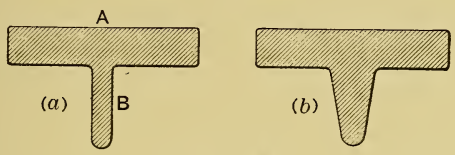


FIG. 26.

reduction of the compressive stress to zero. No tensile stress can be induced until the compressive stress is entirely neutralized. If a tensile force is applied to the casting (a), Fig. 26, it follows that no tensile stress will result in the part *A*, and, therefore, that all the stress will be concentrated on the part *B*. To illustrate this, suppose that a tensile force is applied to a rope, and that half of the strands are tight, and the other half are slack. Stress will result in the strands which are tight until they are strained so much that the others are brought into play, and then the tension is sustained by the whole cross section, provided the strands originally tight are not broken. In the casting, the part *B* sustains the stress until the compression in *A* is neutralized, and its tensile resistance is brought into play. Because of this the unit stress (stress per unit of cross-sectional area sustaining the stress) is very great in the early part of the test, and the deformation, having a proportionate value, is also

much greater than it would be if the whole area of cross section sustained the stress. The stress-deformation diagram, therefore, takes the form shown in Fig. 27; the initial part of the curve representing the concentration of stress on some fraction of the cross-sectional area.

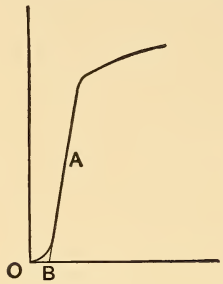


Fig. 27.

If the stress had been gradually relieved at A, the curve would have returned over AB, and OB would be the permanent deformation or "set." If the internal stress in B, Fig. 26, had been sufficiently great, it might have been ruptured before the tensile resistance of A could be brought into action. In any case, the piece could not sustain as great external force as if there had been no internal stress, because there would be no time during the application of force when the whole area of cross section would offer resistance without some part having been previously weakened.

A **varied quality of product** is required from a foundry. The most important requirement for some castings that are not subjected to any considerable stress is that they shall "run sharp"; that is, that they shall take and retain the form of the mold accurately. A very gray silicon iron with its low shrinkage, and with phosphorus enough to give fluidity at casting temperature would serve.

Other castings require to be as strong as possible in tension because, though cast iron is seldom used in direct tension, machine members are often subjected to bending forces which cause both tensile and compressive stress. Still other castings require great compressive strength or great compressive shock-resisting capacity; as, for instance, anvil blocks for power hammers.

Professor Thomas Turner in a paper in the *Trans-*

actions of the Iron and Steel Institute 1885, recorded a study of all available data to determine the best composition of cast iron for given requirements. This study seems to indicate that for greatest softness combined carbon should equal 0.15 per cent, graphite, 3.1 per cent. To obtain this distribution with other substances of average values requires 2.5 per cent silicon. For greatest general and tensile strength combined carbon should equal about 0.5 per cent, graphite from 2.8 to 3 per cent, which corresponds to silicon from 1.4 to 1.8 per cent. For greatest crushing strength combined carbon should be over 1 per cent, graphite under 2.6 per cent, which corresponds to silicon about 0.8 per cent.

In foundry practice it is desirable to use a large amount of "scrap"; partly because "sprues," "gates," "risers," etc., are a necessary product of every heat, and partly because a good deal of scrap is offered for sale at a low price. The effect of remelting iron is to harden it, and therefore, scrap is always of harder grade than the "pig" from which it was originally cast.

The hardening effect of remelting is very clearly shown by some experiments made at the Gleiwitz foundry in Silesia, and quoted by M. Ferd. Gautier in a paper read before the Iron and Steel Institute (see *Journal* of 1886). The results are given in the following table:

Substances with the iron	Original pig iron	After fourth casting	After sixth casting
Graphitic carbon	2.73	2.54	2.08
Combined carbon	0.66	0.80	1.28
Total carbon	3.39	3.34	3.36
Silicon	2.42	1.88	1.16
Manganese	1.09	0.44	0.36
Sulphur	0.04	0.10	0.20
Phosphorus	0.31	0.30	0.30

Thus, the six successive meltings resulted in a decrease in the amount of silicon and manganese, and an increase in the amount of sulphur. (This latter probably was absorbed from the fuel.) Graphitic carbon is decreased and combined carbon is increased; therefore, the combined effect of decrease of silicon and increase of sulphur was greater than the effect of the decrease in manganese. The change necessary to convert this again into soft gray iron is the addition of silicon, provided the amount of sulphur is not too great. The reasons for the hardening effect of remelting are: (*a*) the reduction of the silicon, resulting in the redistribution of carbon; (*b*) the increase of sulphur. Of the substances which are found in combination with iron, silicon is first oxidized, manganese being next in order. Therefore, when iron is melted in the presence of an air blast, some of the silicon is always oxidized, and usually some of the manganese. Iron is melted in the presence of anthracite coal or coke, and hence, there is the possibility of absorption of sulphur. If the total carbon is sufficiently high, the softening of iron can be accomplished very satisfactorily by the addition of a proper amount of ferrosilicon, which usually contains about 10 per cent of silicon. But if total carbon is low, pig iron high in silicon and carbon would serve better, because it would carry a large amount of carbon per unit of silicon.

"Burnt scrap" is cast iron which has been exposed during use to the action of oxygen at high temperatures; as, for instance, old grate-bars, salt-kettles, etc. A portion of the iron becomes iron oxide. When such iron is melted, the iron oxide gives up its oxygen to the silicon, manganese or carbon present, in obedience to the law of affinities; and the results are silica and oxide of manganese, solids which appear as slag, and the gas, carbon monoxide

or carbon dioxide. The reduction of the total carbon will result in harder iron, and the reduction of the silicon will result in the appearance of all the carbon present as combined carbon. This result is so very decided that a whole heat may "run hard" because of the introduction of a comparatively small amount of "burnt scrap." If the effect of burnt scrap is due simply to the fact that the silicon has been removed by the oxygen of the iron oxide, then if it were melted together with a sufficient amount of ferrosilicon, the result would be gray, soft iron. But there might be iron oxide enough present to reduce the total carbon too much; then the silicon could not produce gray iron, because it would not have enough carbon to work with; in this case, carbon as well as silicon would have to be added, and pig iron high in carbon and silicon would serve better than ferrosilicon. The iron oxide, which is seen as rust on the surface of scrap, is effective in the reduction of silicon, etc., upon melting; its effect is of little importance, however, as it is small in amount relatively. It must not be concluded from this that silicon will make good iron out of all kinds of scrap. Some scrap is hopeless because of the presence of sulphur or phosphorus. It must be remembered that the addition of silicon to very gray iron can produce no good results, but rather the reverse, because the carbon is already graphitic, and the only effect of the addition of silicon is its undesirable effect on the iron itself.

CHAPTER IX

STEEL

It has been shown that steel is essentially a combination of iron and carbon, which also contains small amounts of silicon, manganese, sulphur and phosphorus. Steel also may contain other substances such as copper, nickel, chromium, tungsten and vanadium, either from the smelting process or introduced because of desirable effect on physical properties.

The chemical difference between cast iron and steel is in the **amount** present of substances other than iron. The following table gives a chemical comparison of cast iron, the steel used in structures and machines, and tool steel.

Substance	Cast iron, per cent	Machinery and structural steel, per cent	Tool steel, per cent
Carbon	2.5 to 4.5	0.10 to 0.6	0.6 to 1.6
Silicon	0.15 to 2.5	0 to 0.04	0.04 to 0.25
Manganese	0 to 1.5	0.3 to 1.0	0.23 to 0.5
Sulphur	0 to 0.5	0 to 0.06	0.002 to 0.012
Phosphorus	0 to 1.3	0.03 to 0.08	about 0.02

The change from cast iron to machine steel is effected by removing by oxidation all substances other than iron, as completely as possible commercially, and then reducing iron oxide, removing occluded gas and introducing the required amount of carbon. Tool steel is made indirectly from cast iron by more complete purification and intro-

duction of a larger proportion of carbon. Some of the changes in physical properties that accompany these chemical changes may be shown by reference to Fig. 28. AD is the stress deformation diagram of cast iron; AB_2D_2 of machine steel; AB_1D_1 of high-carbon or tool steel.

Change from cast iron to machine steel has increased ultimate strength in the ratio $\frac{M_2N_2}{DE}$; it has increased ductility in the ratio $\frac{AE_2}{AE}$; it has increased ultimate shock resistance in the ratio $\frac{\text{area } AB_2D_2E_2}{\text{area } ADE}$; it has changed a material that may be easily formed by casting into one that is much more difficult to cast and that is usually formed by forging. More complete purification and increase in carbon would change machine steel into tool steel, and strength would be increased in the ratio $\frac{M_1N_1}{M_2N_2}$; ductility would be reduced in the ratio $\frac{AE_1}{AE_2}$; ultimate shock resistance would be changed in the ratio $\frac{AB_1D_1E_1}{AB_2D_2E_2}$. This last change in shock resistance might be either an increase or a decrease, depending on the amount of carbon change.

The field of steel on the equilibrium diagram, Fig. 29, may be assumed as limited on the right by the line JJ_1 at 1.7 per cent carbon, although in special cases the carbon content is higher. Lines of slow cooling of steel may now be followed on this diagram from a, O_1 and b as on page 113.

First. Cooling from a. — Solidification begins at a_2 and is complete at a_3. The solid γ (C) then falls in temperature until a_1 is reached, where separation of β iron begins and continues, causing the point of cooling to follow a_1N to N.

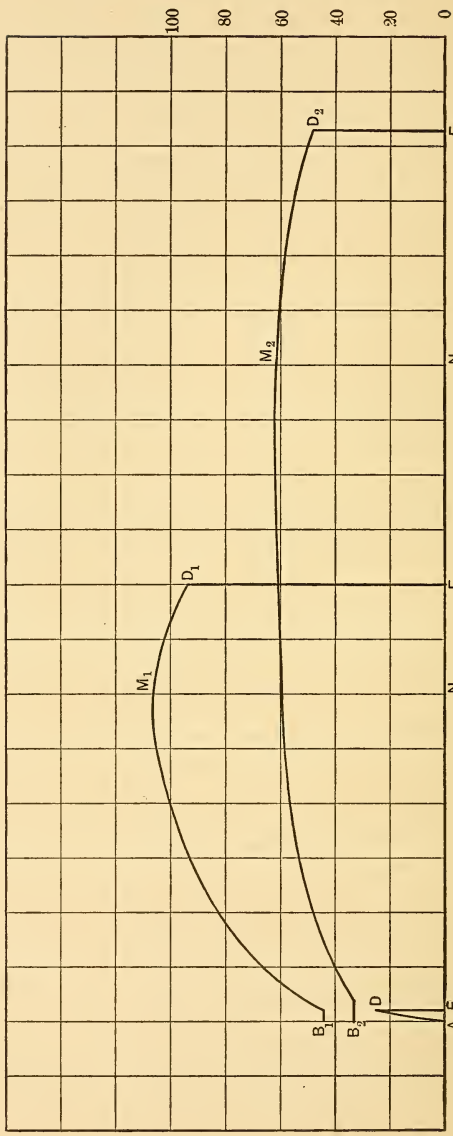


FIG. 28.

At N β iron changes into α iron and with further cooling more of the γ iron of the remaining γ (C) changes into α iron, causing the point of cooling to follow NO to O. On reaching O the mass consists of $\alpha + \gamma$ (C) + (probably) some Fe_3C. At O the γ (C) is changed into the eutectic — very intimately associated crystals of α iron and Fe_3C, the mixture containing 0.9 per cent carbon — which is associated less regularly and less intimately with the α iron that has formed from N to O. Any steel with less than 0.9 per cent carbon will have this qualitative composition, but the greater the proportion of carbon the greater the proportion of eutectic in the cooled steel.

Second. Cooling from O_1. — The cooling point moves vertically from O_1 to O, where the entire solid mass — γ (C) with 0.9 per cent — changes directly into eutectic, $(\alpha + Fe_3C)_{0.9\,C}$. This cooled steel is a homogeneous mass of intimately associated small crystals of α iron and Fe_3C.

Third. Cooling from b. — The cooling point moves through b_2 and b_3 and the mass becomes solid γ (C). At b_1 Fe_3C separates and reduction of carbon in γ (C) causes the cooling point to follow b_1O with continuance of the cementite separation. On reaching O, the mass consists of $\gamma\,(C)_{0.9\,C}$ and Fe_3C; the $\gamma\,(C)_{0.9\,C}$ changes into eutectic and the cooled mass is made up of eutectic plus Fe_3C. Slowly cooled steel with less than 0.9 per cent carbon consists of α plus eutectic in varying proportion. Slowly cooled steel with 0.9 per cent carbon consists wholly of eutectic. Slowly cooled steel with more than 0.9 per cent carbon consists of eutectic plus Fe_3C in varying proportions.

Reference now to Fig. 28 shows — since low-carbon steel is represented by the diagram $AB_2D_2E_2$ and high-carbon steel is represented by the diagram $AB_1D_1E_1$ — that the presence of ferrite, α iron, in large proportion corresponds to high ductility and medium tensile strength;

and that the presence of cementite, Fe_3C, corresponds to high strength and medium ductility. Also, the presence of ferrite corresponds to greater softness, while the presence of cementite corresponds to greater hardness of the mass.

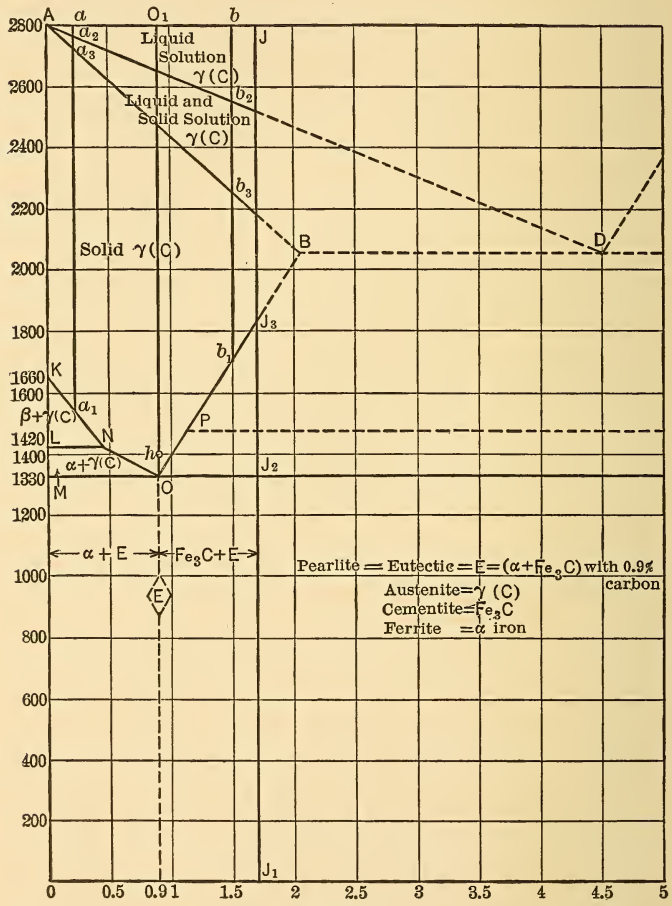


FIG. 29.

When carbon in steel is about 0.5 per cent * or more the steel has the quality of hardening; that is, on quenching in cold water from a full red heat the steel becomes intensely hard and quite brittle; this hardness may be reduced by raising the steel to certain temperatures (the process of tempering) that allow stability tendencies to approach equilibrium. Thus tools can be made of varying hardness suitable for cutting various materials. The quality of hardening is intensified by increase in carbon. See also page 167.

While **carbon** is the chief factor in the control of the physical properties of steel, these properties are also modified by other substances present.

Silicon. — There has been much discussion of the effect of silicon on steel, and the conclusion seems to be that in amounts usually present it is not a seriously injurious element either to strength or ductility. It is not an important question, since with present methods of structural and machine steel manufacture silicon is usually present only as a trace or as a maximum of 0.04 per cent. In steel castings, silicon is often found up to 0.4 per cent without effect on ductility, although tensile strength is considerably increased; it is here, doubtless, because of its capacity to reduce oxides like CO, FeO and Fe_2O_3, formed during melting, and thus to make the castings sound and homogeneous. In tool steel silicon is often present up to 0.25 per cent. But although silicon in relatively small amounts in solution in iron has small effect, with increasing amount the ductility is reduced with increase in brittleness. The fact that ferrite is very ductile in mild steel, less ductile in malleable castings, and very much

* The property of hardening really appears when carbon equals about 0.25 per cent, but the effect which increases with the carbon is not of practical importance with carbon less than 0.5 per cent.

less ductile in cast iron is probably due to the increasing amount of silicon in solid solution.

Manganese. — When steel from the Bessemer or open-hearth process is ready to pour, manganese is added in the form of ferromanganese or spiegeleisen, and its function, as already explained, is, like silicon, to reduce CO, FeO, Fe_2O_3 and to take up free oxygen to form manganese oxide. This oxide is removed with the slag; but a certain amount of manganese goes into solution with the iron and in present practice in structural and machine steels this amount is from 0.7 to 1 per cent. In such amount the manganese prevents cracking of the steel when it is worked hot. With manganese up to 0.6 per cent there seems to be no effect on tensile strength or ductility; from 0.6 to 1 per cent the tensile strength is increased without change of ductility. In tool steel manganese must be kept low, because it tends to cause cracking when the steel is quenched in water for purposes of hardening. If manganese in steel is increased to 2 per cent, the steel is extremely brittle and continues brittle up to about 7 per cent when, with further increase of manganese, strength and ductility both increase until, at 14 per cent manganese with 0.85 per cent carbon, tensile strength becomes about 2.5 times, and ductility about 1.2 times that of good mild steel. The material can be forged hot, but is so hard when cold that it can only be machined by grinding. This special manganese steel is used for machine parts requiring great resistance to wear and to shock.

Sulphur makes steel "red short"; that is, it causes it to crack when rolled hot; it also makes welding difficult. The effect of sulphur on steel when cold has been in doubt, because of conflicting evidence. Of course, if its production of brittleness when hot has resulted in the steel

cooling with cracks, strength and general fitness for use would be less. If the cooled steel is sound the effect of the sulphur might depend on whether it was present as iron sulphide or manganese sulphide. It seems probable that the presence of iron sulphide would tend toward reduced ductility and increased hardness, and it also seems probable that manganese sulphide would have less undesirable effect. It certainly would be desirable to specify sulphur as low as possible without hardship to the steel manufacturer.

Phosphorus tends to cause the formation of coarse, crystalline structure during cooling of steel.* Because of this, or for other reasons, the cooled steel, although its static strength may be somewhat increased, yields more easily to shocks and is unsafe as structural material, that is, it is "cold short." Both sulphur and phosphorus are very undesirable in **tool steel** since the tendency to crack either hot or cold may destroy expensive tools during or after heat treatment.

Arsenic and **copper** are often present in steel, but with modern methods of steel-making the amount of these substances is almost always far within the harmful limit.

Nickel. — The introduction of nickel into steel up to about 8 per cent increases the elastic limit and ultimate strength and also slightly increases ductility. Nickel also seems to increase the hardening effect of a given amount of carbon. Because of this, nickel steel is extensively used as armor plate. In certain cases steel with quite low carbon has about 3.25 per cent nickel added; this gives a ductile steel with a tensile strength of from 60,000 to

* Possibly this is because phosphorus causes extension of the time of cooling and thus gives opportunity for more complete crystallization.

80,000 pounds per square inch. The armor plates made from this steel are "Harveyized"; that is, they are heated to full redness for a long period with the outer surface packed with carbonaceous material; the steel absorbs carbon, and the surface, to the depth of from 1 inch to $1\frac{1}{4}$ inches, becomes high-carbon steel, which hardens on quenching. Thus the body of the plate has the toughness and strength — and therefore the shock-resisting capacity — of low-carbon nickel steel, while the surface has the hardness of hardened high-carbon steel with the intensification of hardness due to the presence of nickel. Nickel steel is often used for structural and machine purposes in places requiring great strength and shock resistance. When welding is necessary nickel should be kept below 2 per cent.

Tungsten added to steel renders it hard and brittle and its chief use is in special steels for cutting tools. See p. 175.

Chromium. Ferrochrome with wide variation of chromium and carbon content is reduced from chrome ore in the blast-furnace, or in carbon-lined crucibles, by strongly heating oxide of iron and oxide of chromium together. Chromium seems to unite with iron in solid solution and also in a chemical compound of iron, chromium and carbon that is exceedingly hard. Chromium seems not only to confer hardness of itself but also to intensify the hardness due to carbon; it also, as shown by careful experiments,* increases the amount of carbon that iron can hold. Thus it may cause a threefold increase in hardening of steel. Because of this chrome steel with Cr about 2 to 2.75 per cent and C 0.9 to 1 per cent is used in projectiles designed for piercing armor-plates.

* See "Steel and Iron for Advanced Students" by Hiorns, Macmillan, p. 309.

These projectiles require very careful heat treatment. Chrome steel is also used for armor-plate, for jaws of crushing machines and for other machine parts requiring great hardness.

Vanadium.—Ferrovanadium is obtained from ores containing vanadium oxide. This oxide, purified by chemical processes, is mixed with iron oxide and powdered pure aluminum, in a crucible with magnesite lining, and ignited; the aluminum combines with the oxygen of the oxides, and the resulting iron and vanadium, at the high temperature produced by combustion of the aluminum, combine to form ferrovanadium. This is introduced into the steel in the ladle after treatment with spiegel or ferromanganese, and any required content of vanadium can thus be obtained.

Vanadium has a very powerful influence upon the physical properties of steel either through its direct influence on the iron or through its indirect influence upon the other substances present. The elastic limit, ultimate strength and shock resistance of steel are very greatly increased by the presence of vanadium in amounts between 0.1 per cent and 0.18 per cent. The steel usually contains manganese and chromium in addition to the carbon, and frequently nickel also.

A standard vanadium steel has the following composition:

	Per cent
Carbon	0.25 to 0.3
Manganese	0.5
Chromium	1.0
Vanadium	0.17

This steel gives values about as follows:

Heat treatment	Elastic limit, lb. per sq. in.	Ultimate strength, lb. per sq. in.	Elongation in 2 inches, per cent
Annealed	65,000	90,000	28
Oil tempered	125,000	136,000	18
For mild carbon steel corresponding values	38,000	70,000	32

Impact tests also show very distinct gain in shock resistance due to the presence of vanadium.

Vanadium-nickel and vanadium-chrome-nickel steels are also used where great strength, lightness and shock resistance are prime requirements; the latter steels have a percentage range about as follows:

	Per cent
Carbon	0.25 to 0.45
Manganese	0.5 to 0.7
Nickel	1 to 1.5
Chromium	0.6 to 0.8
Vanadium	about 0.18.

There may be **internal stresses** in **forged material,** similar to those resulting in cast material from unequal shrinkage. They are usually the result of working the material too cold. To illustrate: when a thin piece of ductile material is laid on an anvil and struck with a hammer, the piece is made thinner and longer and broader. Suppose now that the piece is thick instead of thin, and that it receives a blow as before: the influence of the blow extends only a little way into the material, and the surface is made longer and broader. Since its extension is resisted by the part which is uninfluenced by the blow, the material at the surface is put in compression, and the

inner portion in tension. The initial part of the stress-deformation diagram would be as shown in Fig. 27. If the working is done at a red heat, the material is soft and weak, and, therefore, yields to the stresses introduced by the hammering or rolling, and equilibrium results.

Effect of lack of homogeneousness of material on the stress-deformation diagram. — In the manufacture of wrought iron the elements of the piles of "muck-bar" or scrap are drawn out in rolling into long lines of crystals, which are separated by more or less slag or oxide of iron. Since the pile may be made up of bars or scrap of entirely different quality, the structure may lack homogeneousness. This has a tendency to modify the form of stress-deformation diagram. Suppose, for example, that a test piece of wrought iron has half of its area of cross section of a material whose elastic limit is at E^1, Fig. 30, and that the other half of the cross section is of material whose elastic limit is at E. Let a constantly increasing tensile force be applied to this test piece. When the stress reaches the value represented by the ordinate E, the weaker part of the material begins to yield more rapidly than the stronger part, and the unit stress on the stronger part is very greatly increased, its elastic limit is exceeded, it also yields, and the curve takes the form shown, running nearly parallel to the axis of X until the stress is again distributed over the entire surface of the cross section; then the curve rises continuously until the maximum stress is reached. Steel may also show this irregularity, since different parts of the forging may have different elastic limit, because of different heat treatment, different hot working or superficial cold working.

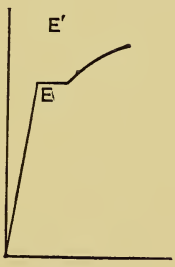


Fig. 30.

Effect of cold working. — When a piece of ductile material is strained beyond its elastic limit, the character of the material is greatly changed. If, after a short interval of rest, it is tested again, its elastic limit and elastic resilience will be found to be higher, its tensile strength greater and its ductility and ultimate resilience less. The stiffness will be but slightly changed, if at all. By cold working, i.e., by any means that gives permanent set to cold material, the elastic range is increased, the piece is made stronger and better able to resist shocks within the elastic limit, but less ductile, and less able to resist shocks exceeding the elastic limit. These changes are shown graphically in Fig. 31. The stress-deformation diagram $OEABCD$ is such as would usually result from a test of a ductile material, like mild steel or wrought iron. On reaching some point, as E_1, stress is gradually relieved, and the curve descends to the X axis at O_1. On reapplication of tensile force the curve rises along the line O_1E_1 nearly parallel to OE. The elastic limit is now at E_1, a point much higher than the original elastic limit E. The curve then continues, a little higher than it would if the stress had not been discontinued, until the maximum is reached at H.*

If the force could have been instantly reapplied at O_1, the line GHJ would probably have coincided with ABC, because the change is a function of the time of resting, after relief of stress. $OEABCD$ may be considered the diagram of one material, and O_1E_1GHJ the diagram of

* That the maximum strength is increased has been demonstrated by Bauschinger. He first broke a long test piece by tensile force. It was of uniform cross section, and hence all of its parts must have been strained well past the elastic limit. He then broke one of the pieces and found increased strength. This was repeated six times, and each repetition resulted in increased strength.

another material. It is as if a new test began at O_1. Let a represent the first diagram, and b the second. The elastic range of b, represented by O_1E_1, is greater than that of a, represented by OE. The elastic resilience of b, represented by the area $O_1E_1F_1$, is greater than that of a, represented by OEF. Experiment has proved that the points B and C are not changed in their relation to the axis of Y by the relief of stress; and therefore the ductility of a, represented by OD, is greater than the ductility of b, represented by O_1D. The ultimate resilience, proportional to the total area under the curve, is evidently greater in a than in b. O_1E_1 is nearly parallel to OE, and hence rigidity is nearly the same for both.

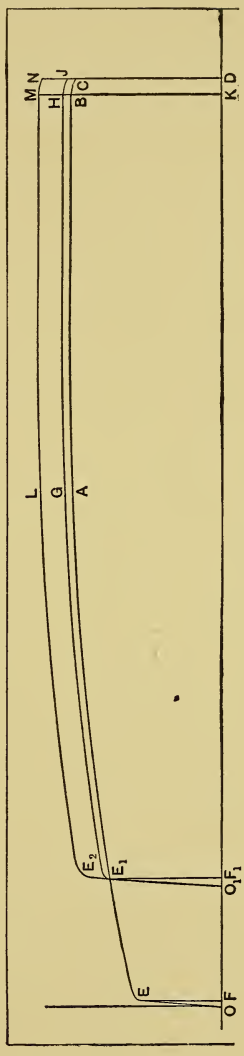


FIG. 31.

If, instead of the almost immediate reapplication of force, a considerable interval of rest had been allowed, say twenty-four hours, the elastic limit and ultimate strength would have been still further raised, and the diagram would be like O_1E_2LMN. If stress were not discontinued until the maximum had been nearly reached, the strained material would resemble a very brittle material.

It may be stated as a conclusion warranted by experiment (see *Trans. Am. Soc. Civil Engineers*, Vol. XXIV, p. 159), that stress of any character beyond the elastic limit will render a ductile material stronger and less ductile under stress of any other character. **Annealing removes these effects almost completely.** The process of "cold rolling," by which shafting is produced, illustrates the alterations of the qualities of ductile material due to stress beyond the elastic limit. In this process iron is passed cold through highly finished rolls, under intense pressure. The rolled piece has its length increased and its cross section reduced, and therefore, since the material takes a "set," it must be strained by the treatment past its elastic limit.

Professor Thurston made a series of tests to determine the effect of cold rolling upon iron. His experiments show that there results from the process: (*a*) an increase in tensile strength of from 25 to 40 per cent; (*b*) an elevation of the elastic limit of from 80 to 125 per cent; (*c*) an increase of elastic resilience of from 300 to 400 per cent; (*d*) a decrease in ductility of about 75 per cent; and (*e*) a decrease of ultimate resilience of about 40 per cent. If, therefore, the product of the process is required to withstand stress (and especially shock), which cannot exceed the elastic limit, it is far better than the untreated iron; but if there is a possibility of shock exceeding the elastic limit, the unrolled iron might be better.

The process of "wire-drawing," i.e., reducing the size of wire with increased length by drawing it cold through dies, produces the same result as cold rolling, the wire requiring frequent annealing to restore ductility.

The effect of repeated stress. — Between the years 1859 and 1870, A. Wöhler planned and executed a series of experiments for the Prussian Government, to determine

the laws governing the behavior of metals under repeated stress. By means of his machines, forces of known value producing tensile, compressive, torsional or transverse stress could be applied with indefinite repetition, until rupture occurred, or until it was considered proved that indefinite repetition of stress could not produce rupture. He formulated a law from the experimental work, which in substance is as follows:

Material may be broken by repeated application of a force which would fail to produce rupture by a single application. The breaking is a function of range of stress; and as the recurring stress increases, the range necessary to produce rupture decreases. If the stress is reversed, the range equals the sum of positive and negative stress.

The experimental work of Wöhler was amplified and supplemented by Professor Bauschinger of Munich. He drew the following conclusions from his experimental work:

(*a*) "With repeated tensile stresses, whose lower limit was zero, and whose upper limit was near the original elastic limit, rupture did not occur with from 5 to 16 million repetitions." He cautions the designer that this will not hold for defective material, i.e., a factor of safety must still be used for this reason; and that the elastic limit of the material must be carefully determined, because it may have been artificially raised by cold working, in which case it does not accurately represent the material. This original elastic limit may be determined by testing a piece of the material after careful annealing.

(*b*) "With often repeated stresses, varying between zero and an upper stress, which is in the neighborhood of or above the original elastic limit, the latter is raised even

above, often far above, the upper limit of stress, and it is raised higher as the number of repetitions of stress increases, without, however, a known limiting value L, being exceeded."

(*c*) "Repeated stresses, between zero and an upper limit below L, do not cause rupture; but if the upper limit is above L, rupture will occur after a limited number of repetitions."

From this it would follow that keeping the **range** of repeated stress within the original elastic limit would insure safety against rupture with any number of repetitions whatever. But there is a question whether the experimenters have proved their case, since they dealt necessarily with a finite number of stress-cycles. The conclusion that rupture with repeated stress is a function of range of stress seems to be sound; but Professor Bauschinger's conclusion that there is a limit of range within which there is absolute safety from repeated-stress rupture seems questionable. A perfectly elastic material is one that returns exactly to its initial condition after deformation under stress; there is question whether any engineering material is perfectly elastic for any range whatever, even under small, slowly applied stress.

There is evidence * that **any** change of stress in iron causes the magnetic and thermo-electric properties to change in an irreversible way, and, to quote Professor Ewing: † "Every variation leaves its mark on the quality of the piece; the actual quality at any time is a function of all the states of stress in which the piece has previously been placed. It can scarcely be doubted that sufficiently refined methods of experiment would detect a similar want of reversibility in the mechanical effects of stress."

* See papers by Prof. J. A. Ewing, *Phil. Trans.*, 1885–1886.

† See his excellent book, "The Strength of Materials," p. 55.

Professor Ewing also cites experiments by Lord Kelvin which show that* "repeated changes of stress have a cumulative effect in reducing elasticity, while Wöhler's experiments show that they also have a cumulative effect in reducing strength. It may be conjectured that repeated strains induce a change in molecular structure of which the fatigue in strength and the fatigue in elasticity are two manifestations."

Annealing restores both original strength and elasticity; rest restores original elasticity and, as recently proved, † restores strength also.

In the stress-elongation diagram of cast iron, Fig. 18, stress was relieved at *C* and the path of diminishing stress is *CDE*, while the path of reapplied stress is *EFC*. These two paths enclose an area which, on this diagram of force-space coördinates, represents work. If the up and down paths were identical, there would be no enclosed area and the work done by the increasing force would be completely restored on relief of stress in the same energy form, and there would remain in the material no permanent result of the work done; the material would be in exactly the same condition before and after the application of force and hence would be perfectly elastic. This is what is called a reversible process. But if the up and down paths enclose an area, the process is irreversible, the material is not perfectly elastic and an amount of work proportional to the area fails of return in its original energy form; it is converted into heat by resistance of the material to molecular change, the heat is radiated away and the resulting molecular change remains. Repetition of this cycle — called the hysteresis cycle — does

* Ewing's "The Strength of Materials," p. 56.

† See "Materials of Construction," by Professor George B. Upton, John Wiley & Sons.

more internal work to cause molecular change, and with continued repetition the material would be destroyed. Wherever there is a hysteresis loop with repeated stress, the work of destruction is under way. The length of the loop corresponds to the range of stress; the width of the loop corresponds to amplitude of molecular displacement; and the area of the loop, proportional to length and width, corresponds to the work done to produce molecular change, and hence to the destroying agency. Therefore, increase in range of repeated stress increases the destroying agency and hence reduces the number of cycles to cause fracture. It is found experimentally that the width of the loop increases with the number of cycles, and hence the destroying agency has an increasing value.

Though the ordinary methods of test do not show a hysteresis cycle within the so-called elastic limit of steel, yet more refined methods disclose such a loop,* and make it extremely probable that repeated stress, even within the original elastic limit, would cause rupture with a **sufficient number of repetitions.** Ordinarily machines grow obsolete or wear out and are discarded long before fatigue failure occurs.

There is another effect of repeated stress that is independent of the effect on molecular structure. If very minute flaws exist in the material, or if continuity is broken by small particles of foreign substance, the tendency of repeated stress is to increase the size of the imperfections and a number of these extending micro-flaws might join to produce a large crack and eventually to cause fracture. Larger hidden flaws might, of course, be extended similarly with the same result.

* The phenomenon known to physicists as "elastic after-effects" shows this.

Effect of temperature on steel. Many experiments by various careful observers show that when steel is heated to about 500° F. its tensile strength begins to decrease, and that at the temperature of incipient redness, about 1000° F., its value is less than half the value at air temperature. It is also known that prolonged and repeated exposure to temperatures of 150° F., or higher, produces reduction of ductility, so that to insure safety periodical annealing is necessary, as in case of chains of cranes for lifting ladles of molten steel or hot ingots.

Factors of safety. — Machine stress-members may fail, not only because of repeated stress, but also because of:

(*a*) Flaws, or other imperfections in the material;
(*b*) Internal stresses;
(*c*) Unhomogeneous material;
(*d*) Shocks;
(*e*) Stresses which cannot be estimated.

To cover all these a factor of safety is used; i.e., the working unit stress is equal to the ultimate unit strength of the material, divided by a number which is called the factor of safety.

Materials are so various in their qualities, and the conditions to which they are subjected as machine stress members are so different, that it is impossible to give any value for a factor of safety to cover all cases.

For ductile resilient material, like mild steel used in building-frames, roof-trusses, bridges, etc., a low value may be used for the factor of safety, because *b*, *c* and *d* given above may be practically eliminated by proper specifications and careful inspection, and because the loads are known.

But in machines the conditions are dynamic, and it is more difficult to estimate stresses, especially when acci-

dental increases of velocity are possible, or when lost motion, due to wear or imperfect adjustment, enable moving parts to deliver blows to other parts.

For unresilient or brittle materials, like cast iron, the factor of safety needs to be larger, not only because of less shock-resisting capacity, but because shrinkage stresses are always present and there is, in many cases, danger of blow holes or spongy sections. The weakening effect of these varies with the size and form of the member, and with the conditions of casting. Hence the factor of safety must be determined in each case by the judgment of the designer.

CHAPTER X

HEAT TREATMENT OF STEEL

When molten steel cools slowly to air temperature its structure is coarsely crystalline; the size of the crystals increases somewhat with the time of cooling and with the amount of carbon present. The steel of a tool-steel ingot is coarse, brittle and unfit for service. The steel of a mild steel ingot — though the coarse structure is less marked — also needs treatment to change structure to give required strength and ductility. The finest possible structure of steel corresponds to highest strength, ductility and shock resistance; this structure may be produced by **heat treatment, which consists of heating and cooling through certain temperature ranges and with certain rates of temperature change.**

The structure of steel, whatever it may be at air temperature, is changed to the finest possible crystal size when the increasing temperature reaches about 1330° F., corresponding to the line *MO*, Fig. 29. If the increase in temperature continues from 1330°, the crystal size grows steadily larger until fusion begins and the size thus reached is retained, whatever the method of cooling; if, after reaching 1330°, the temperature is allowed to fall slowly, the crystal size increases until the temperature of disappearing redness is reached and this size is retained independently of the method of cooling. Increase in crystal size is undesirable when high shock resistance is required, and, therefore, whatever the purpose of heat

treatment it should produce the finest structure possible under the circumstances in steel that is required to resist shock.

When points representing cooling steel pass slowly through the territory, Fig. 29, bounded above by the line $KNOJ_3$ and below by the line MOJ_2, the steel changes from solid γ (C), (austenite) to eutectic $(\alpha + Fe_3C)_{0.9\,C}$ mixed, according to the carbon content, with excess of either ferrite (α iron) or cementite (Fe_3C). Careful observation and reasoning by many eminent metallurgists seem to show that during this change the steel passes through three intermediate states with varying physical properties. The names given to steel in these successive states are austenite, the original γ (C), martensite, troostite and sorbite.

Austenite is soft and ductile, with medium strength and high shock resistance.

Martensite is intensely hard, strong under steady stress, but with low shock resistance.

Troostite has medium hardness and is strong, ductile and tough.

Sorbite is nearly as soft as austenite and is strong, ductile and tough.

With slow cooling, austenite would change through this series and become sorbite and the change would be complete. But during this change austenite does not change wholly into martensite and then wholly into troostite; the changes overlap so that before all austenite has become martensite the formation of troostite out of martensite has begun and all three are present in varying amounts. By the time austenite has disappeared the formation of sorbite out of troostite has begun, and martensite, troostite and sorbite are present in varying amounts; then

martensite and troostite disappear in order, leaving sorbite alone. If the cooling could be suddenly checked at any temperature and held there to establish equilibrium, the steel could be held in the state corresponding to that temperature and it would have physical properties depending on the proportions of steel-carbon forms present.

Objects of heat treatment are as follows:

1. To relieve internal stress due to cooling or mechanical working and to produce a soft steel suitable for machining; this is called **annealing.**

2. To restore fine grain to steel that has been made coarse by overheating; this is also called **annealing,** or sometimes **refining.**

3. To produce a very hard steel for cutting edges of tools or for wearing surfaces; this is called **hardening.**

4. To reduce the hardness produced by the hardening process to any desired value and at the same time partially to restore ductility and reduce brittleness; this is called **tempering.**

5. To render stress members of machines tough and shock resistant for severe service. This is sometimes called **toughening.**

6. To raise the elastic-limit so that in case of springs there may be large yielding without permanent set; this is called **spring tempering.**

The list will now be considered in detail.

1. **Annealing.** — Stresses due to cooling, or to mechanical working at too low a temperature, may be relieved by heating to about 900° F., a temperature just below incipient redness, and cooling slowly. The material becomes soft enough at this temperature to yield to internal stresses and to take a new adjustment in equilibrium. Also, if there is any result of a previous hardening

process, it is entirely removed before reaching 900° F. If very great softness is required for machining, the steel is cooled very slowly from about 1600° F. This, of course, produces coarse grain which must be refined, if necessary, for shock resistance, by method 2 or 5.

2. **Annealing or refining.** — But if the steel had been cooled from some temperature above the line *MO*, the size of its crystal structure would have been enlarged beyond the size corresponding to *MO*; the higher the temperature from which the cooling took place the larger the crystal size. This size of crystal with its accompanying brittleness remains unchanged during cooling and during reheating until *MO* is reached, when it is changed quite suddenly and irresistibly to very fine crystal size. With further increase of temperature the crystals grow as before. In order to fully restore the fine structure from the coarse structure due to overheating, it is necessary to raise the temperature to the limit set by the line *KNO* so that change to γ (C) shall be complete.* Hence a higher temperature is necessary to restore low-carbon or high-carbon steel than to restore steel with 0.9 per cent carbon; in fact with the eutectic proportion, 0.9 per cent carbon, it is only necessary to heat to *MO*.† After heating the steel above $KNOJ_3$, if it is caused to cool very slowly by packing in sand or ashes, the change from austenite to sorbite becomes complete, and, although the crystal size increases during cooling, yet it is the finest structure that fully annealed steel can have. This steel

* It is sometimes necessary to repeat the reheating to insure complete refining.

† The range of the temperature of change during heating is somewhat higher than during cooling and hence the temperature is raised in practice from 80° to 90° F. higher than that corresponding to the diagram and is held for about fifteen minutes at this temperature to insure complete change to γ (C).

is thus free from internal stresses, and it is soft * and ductile with medium tensile strength.

3. **Hardening.** — Consider that steel with 0.9 per cent C is raised to a temperature of 1400° F., corresponding to *h*, Fig. 29. After passing above *O* it changes into γ (C). Suppose now that the steel is "quenched," that is, immersed in agitated cold water. This sudden cooling tends to check the change of austenite through martensite and troostite to sorbite. The ordinary methods of quenching † cannot hold the steel in the austenite form, and in the quenched steel martensite is usually the predominating form with a considerable amount of troostite and very small amounts of austenite and sorbite. The steel, therefore, has the qualities of the dominant martensite and is hard enough to scratch glass, and, although statically strong, is brittle. Steel fully hardened in this way is usually too hard and brittle for service and must be further treated by the process of tempering.

4. **Tempering.** — If the hardened steel is raised in temperature a faint yellow color appears at about 425° F., on any portion of its surface that has been polished, and at this temperature the tendency to change through the a.-m.-t.-s.‡ series begins to be active and the amount of martensite decreases while troostite and sorbite increase, with corresponding softening of the steel and with decrease in brittleness.

At 475° F. the surface color of the steel becomes full yellow.

* Though not with the maximum softness of about 1600° cooling temperature.

† The rate of cooling depends not only on the quantity and temperature of the water, but also on the relation of cooling surface to volume of the steel; hence thick bars would cool more slowly than thin bars.

‡ Austenite-martensite-troostite-sorbite series.

At 540° F. the surface color of the steel becomes purple.

At 560° F. the surface color of the steel becomes bright blue.

At 600° F. the surface color of the steel becomes dark blue.

With these increases in temperature there is accompanying increase of power of the steel to change through the a.-m.-t.-s. series toward sorbite, and if the steel is held for a few minutes at a temperature corresponding to any one of these colors, there will be a reduction in hardness which corresponds to the temperature.

5. **Toughening.** — When steel is annealed by heating to a temperature slightly above $KNOJ_3$ and cooling very slowly to air temperature the crystal size increases throughout the range down to about 1000° F. and with this increase there is loss of ductility and shock resistance. Let the temperature above $KNOJ_3$ that gives full transformation into γ (C) be called W, and the temperature of incipient redness, about 1000° F., be called V. The increase in crystal size and in brittleness occurs between W and V; the change from austenite to sorbite with resulting softness and ductility may occur entirely below V. Therefore if steel is heated to W and quenched to V, the increase in crystal size will be suppressed, or at least greatly diminished; and if the steel is allowed to cool slowly from V to air temperature the a.-m.-t.-s. series can be completed during the cooling. Both the holding of fine grain and the completion of the a.-m.-t.-s. series increase strength with nearly constant ductility and hence this double process toughens the steel. This process was first conceived by Mr. John Coffin and applied to car axles at the Cambria Steel Works at Johnstown, Pa., with remarkable results. It is now very generally used

by manufacturers for steel that is to be subjected to severe and repeated shocks.

6. **Spring tempering.** — When steel is heated to *W* and quenched in a medium like oil, which cools it less rapidly than water, the a.-m.-t.-s. series is more nearly complete because of longer time, and the steel is less hard and more ductile; but the martensite is still a potent factor in determining the physical properties of the steel and it not only hardens and reduces ductility, but it also raises the elastic limit and thus gives a wider range of yielding within the elastic limit. By regulation of the time of quenching and sometimes by subsequent tempering, it is possible to control the steel-carbon states so as to give the required elastic range for all kinds of spring service and also to hold brittleness within necessary limits.

Hot working of steel. — When steel is heated so that its representative point on the equilibrium diagram, Fig. 29, is in the territory above $KNOJ_3$, the structure is coarse, the size of grain being nearly proportional to the temperature above MOJ_2, and the grain size persists during cooling to air temperature; hence steel cooled from high temperatures is coarse-grained and brittle. But if steel at these high temperatures is mechanically worked so that its dimensions are changed, as by rolling or hammering, the coarse crystals are broken up and the grain becomes fine. If the mechanical working ceases while the steel is still at high temperature, the crystals increase again to the size corresponding to the temperature. If, however, the mechanical working continues until the temperature is reduced to about 900° F., "black heat," the steel will have a very fine grain with corresponding physical properties. The coarsely crystalline ingots from the crucible steel process are heated and hammered into commercial bars, and the hammering continues, the

intensity of blows decreasing with temperature, until black heat is reached, and the steel is thus given very fine grain.

Annealing forgings. — In complex forgings, however, it is impossible to work all parts uniformly from forging heat to black heat; therefore some parts of the forging will cool from high temperature without working and hence with coarse grain, while other parts will have the fine grain due to careful working. This forging can be given a uniform grain by heating uniformly to the temperature W and cooling very slowly. This uniform grain, however, will not have minimum size since it has had opportunity to grow through the temperature range W to V. The ideal treatment for this forging if it is to endure severe and repeated shock is to heat uniformly to W, to quench as suddenly as possible * to V, and then allow slow cooling to air temperature. This insures fine grain and completion of the a.-m.-t.-s. series, thus giving a maximum of toughness and shock resistance.

Annealing steel castings. — Since steel castings cool from a molten state, and since the cooling must be relatively slow, it follows that they must have a coarse grain. Moreover shrinkage stresses are greater in steel castings than in cast iron because of the higher casting temperature, and hence steel castings should be annealed to relieve stress and to refine grain if the best results are to be produced in resisting stress and shock. Either the annealing or toughening process may be used, but the latter will produce better results.

Case-hardening. — Many steel forms require a very hard surface to resist wear or impact, and a tough core to resist fracture. Forms of low-carbon steel having the required core properties may be case-hardened for such

* Complex forgings may require a slower cooling medium than water, like oil or moving air, to prevent over-stress.

purposes. The forms are packed in carbonaceous material, like wood or bone-charcoal, in boxes from which air is excluded, and the temperature is raised to full redness, and maintained for a sufficient time to produce the desired result. Carbon migrates into the steel and goes into solid solution at this temperature. The depth of the effect and the percentage of carbon depends on the temperature and the time of exposure. The surface is thus converted into high-carbon steel while the core remains unchanged. The steel form quenched from the case-hardening process has a hardened surface, but since the carbonizing temperature is higher than is needed for the hardening, the grain will be coarser than is desirable and it would be better to cool slowly, reheat to *W* and quench, thus getting the desired hardness with fine grain and toughness. Case-hardened steel pieces may be heat treated exactly like high-carbon steel; they may be annealed, hardened and tempered.

The process of "Harveyizing" is really case-hardening applied to large armor-plates.

Mild steel is often converted into high-carbon steel at its surface by immersion for some time in a molten bath of potassium cyanide, KCN, which yields up its carbon to the steel.

High-speed tool steels. — The output of a cutting-tool of carbon steel is limited because of the limit to cutting speed. The work done in removing metal as chips is practically all transformed into heat which raises the temperature of the tool, of the chips and of the piece from which the chips are cut. This heat is radiated away and when equilibrium is established between heat development and heat radiation the cutting tool will have a definite temperature. If the cutting speed is increased, the work — and hence the heat developed — is increased

proportionately, and the temperature of the cutting tool, etc., must rise in order that radiation shall increase to dispose of the increased heat developed. With a given material to cut, and with given conditions of feed and depth of cut, there is, therefore, a definite relation between the cutting speed and the temperature of cutting tool; hence the output of a cutting tool is a function of the temperature that it can endure safely.

If the temperature of a hardened, tempered carbon-steel tool is raised in service above that at which it was tempered the temper will be further drawn, the edge will be softened and will fail. The limits of temperature for such tools is about 450° F. Modern high-speed tool steels hold an edge satisfactorily at red heat.

About 1860–70 Robert Mushet of the Titanic Steel Company in England discovered that if steel contained tungsten, chromium and manganese, together with high carbon and the usual other substances, this alloy cooled slowly in air was nearly as hard as carbon steel quenched in water. This "Mushet" steel or self-hardening steel or air-hardening steel, as it was variously called, was used for many years because it increased the possible cutting speed — since its temper could not be drawn.

Messrs. Frederick W. Taylor and Maunsel White of the Bethlehem Steel Works carried out a masterly series of investigations * which led them to the invention of modern high-speed steels and which by increasing the cutting efficiency of tool steel from 100 to 200 per cent has revolutionized machine shop practice.

The development of these steels can be shown best by reproducing a table from Mr. Taylor's article. This table gives the composition and cutting speed of four

* See *Transactions of Am. Soc. Mech'l Eng's*, Vol. XXVIII, on "The Art of Cutting Metals," by F. W. Taylor, p. 31.

steels that are representative, as Mr. Taylor says, of four eras in the development of metal cutting tools.

The first is Jessop steel which may represent the era of carbon-steel tools; the second is Mushet steel, the first of the self-hardening steels; the third is the original Taylor-White steel, the first of the high-speed steels; while the fourth was the best modern high-speed steel in 1906 when Mr. Taylor's article was written.

Kind of steel	Tungsten, per cent	Chromium, per cent	Carbon, per cent	Manganese, per cent	Vanadium, per cent	Silicon, per cent	Phosphorus, per cent	Sulphur, per cent	Speed in feet per minute cutting medium steel
Jessop carbon.....	....	....	1.047	0.189	....	0.206	0.017	0.017	16
Mushet.....	5.44	0.398	2.15	1.578	....	1.044	....	....	26
Original Taylor-White	8	3.8	1.85	0.3	....	0.15	0.025	0.03	58 to 61
Best modern high speed 1906.....	18.91	5.47	0.67	0.11	0.29	0.043	.....	.....	99

Thus the cutting speed was increased over sixfold. Progress from Mushet steel to best modern high-speed steel shows very great increase in tungsten and chromium, very great decrease in carbon, manganese and silicon, and the introduction of the new element vanadium.

Study of the high-speed steels by the equilibrium diagram is beyond the scope of this book, but the heat treatment necessary for best results is as follows:*

The cutting end of the tool is first raised slowly and uniformly to a bright cherry-red; then it is raised as rapidly as possible to a temperature at which the edges of the tool begin to fuse; the whole end of the tool must be raised uniformly to this temperature of incipient fusion.

* From Mr. Taylor's paper.

The tool is then plunged into a molten lead bath at a temperature of 1150° F., where the tool temperature is very rapidly reduced to, or below, 1550° F. The amount of lead in the bath must be enough so that its temperature shall not be sensibly raised by the heat given out by the cooling tool, because it is important that the temperature of the tool shall not be raised at all, at any time during this cooling process. From the temperature of 1550° F., or lower, the cooling to air temperature may be fast or slow without harmful result. The process thus far is called the "high" heat treatment.

The tool is then given "low" heat treatment as follows: it is heated, slowly at first, and then, through the agency of a lead bath which is kept at about 1150° F.; to a temperature that must be above 700° F., and below 1240° F.; it is held at this temperature about five minutes and then cooled either in an air-blast or simply by exposure to still air. The tool is then ready for use and it will hold its cutting edge after it has grown red hot under the cut. It is important that the temperature shall not exceed 1240° F. during this low heat treatment because there would result great reduction of the quality of "red-hardness."

CHAPTER XI

NON-FERROUS ALLOYS

When two metals are melted together, one usually takes the other into liquid solution, or perhaps the two metals take each other mutually into solution, with wide range of composition. The temperature of solidification of the preponderating metal is sometimes reduced by the introduction of the other metal, as when an increasing amount of zinc is added to copper; or the solidification temperature may be increased, as when the process is reversed and increasing amounts of copper are added to zinc. When the cooling alloy solidifies, the solution may continue into the solid state; or the alloy constituents may separate completely from each other; or chemical combination of portions of the constituents may occur; or there may be combinations of these results. In most of the alloys that are useful to the engineer, the solid is composed of one or more crystallized solutions. In some cases there are several different possible solutions, and the ones that form depend on the proportions of the constituents present.

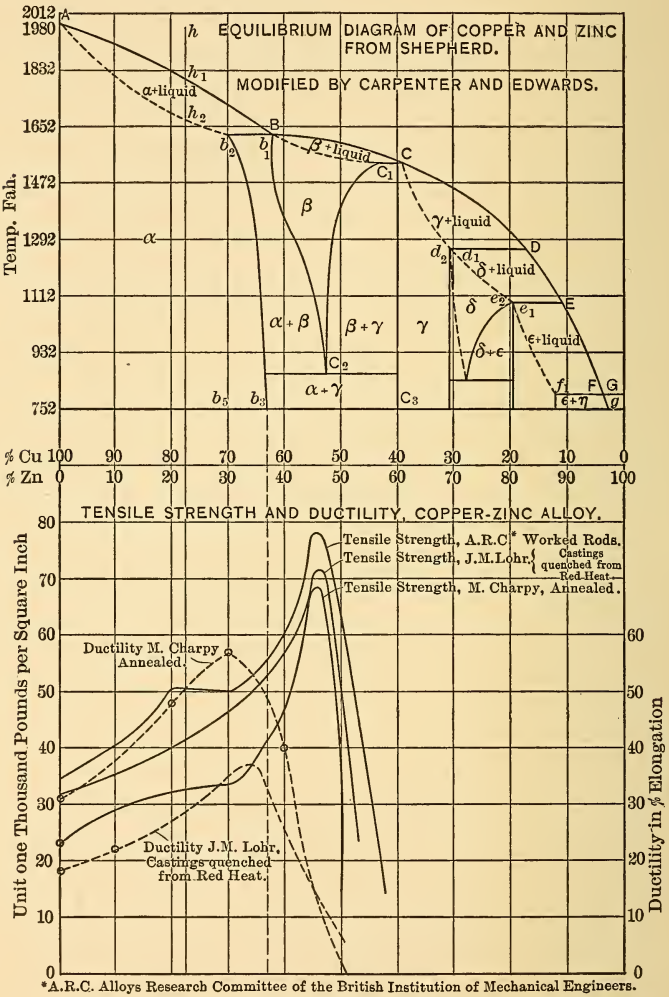
Alloys with **copper** as chief constituent are most important in engineering work.

The **copper-zinc alloys** are usually called **brass.**

In the upper part of Fig. 32, the brass equilibrium diagram * is shown with the entire range from copper

* This diagram is from a paper on the Constitution of the Copper Zinc Alloys by Mr. E. M. Shepherd in the *Journal of Physical Chemistry*, Vol. VIII, p. 421.

100 per cent to zinc 100 per cent. In the lower part of Fig. 32 are curves that show strength and ductility of the



*A.R.C. Alloys Research Committee of the British Institution of Mechanical Engineers.

FIG. 32.

alloys of varying composition in the forms of castings, worked rods and annealed alloy.

In the equilibrium diagram the curve of incipient solidification consists of six branches, and there are six corresponding solid solutions or phases of copper and zinc. The branches and corresponding phases are as follows:

Branch	Phase
AB	α
BC	β
CD	γ
DE	δ
EF	ϵ
FG	η

A liquid solution of zinc in copper, represented by the point h on the diagram, may be followed in cooling. On reaching h_1 the solution begins to solidify, beginning with the formation of crystals low in zinc and continuing with the formation of crystals with steadily increasing zinc content until h_2 is reached and solidification is complete. With sufficiently slow cooling diffusion probably would produce a homogeneous solid solution of α crystals. The result would be the same anywhere from A and b_2 (copper 100 per cent to 70 per cent) except that the proportion of zinc would steadily increase and color would change gradually from copper-red to light yellow at about 90 per cent copper, and to dark yellow at b_2 with copper 70 per cent.

Reference to the lower curves shows that addition of zinc to copper up to 30 per cent Zn, producing the α solid solution, gives increase in strength and in ductility, and hence in shock resistance, whether the resulting brass is in the form of castings, annealed brass or worked rods. Also any solution between b_5 and b_3 (copper 70 per cent and 64 per cent) in cooling eventually enters the field where α is the stable solid solution, and this range is characterized by high strength and ductility — and hence

high shock resistance. Between b_3 and C_3 (copper 64 per cent to 40 per cent) equilibrium corresponds to a mixture of α and γ solid solutions, and through this range there is first a steep rise in strength up to about 53 per cent copper and a steep drop in ductility to zero at copper about 50 per cent, and then the strength falls very rapidly. This change is probably due first to the influence of increasing $\alpha + \gamma$ eutectic and later to increasing amount of free γ solution. From 50 per cent copper to the pure zinc end of the range the alloys are worthless to the engineer.

Copper-zinc within the range (copper 63 per cent to 56 per cent) is sometimes called Muntz metal; this alloy can be rolled or forged at a red heat, that is, in the field BC_2C_1, where it is in the form of β solution; it is used for sheathing and fastenings for ships. The lower diagram shows that with this alloy there is some sacrifice of ductility to gain strength.

For castings the alloy usually contains copper about 67 per cent, while for ingots to be drawn into tubes or wire the copper is about 70 per cent, corresponding nearly to maximum ductility.

Cold working breaks down the crystalline structure of brass, increasing strength and brittleness, and during the processes of drawing tubes or wire the brass must be frequently annealed to restore ductility. The effect of cold working is obvious on comparison of the tensile strength curve of worked rods with the curve of annealed brass in Fig. 32. This increase in strength must have been accompanied by reduction of ductility.

The annealing is accomplished by heating the brass to a temperature between 1100° F. and 1200° F. where recrystallization occurs. Quenching from this temperature tends to hold crystals small whereas they increase in size

with slow cooling. With either method of cooling the alloy is soft.

The quality of brass is often affected by the presence of substances other than copper and zinc; these substances may enter as impurities with one of the constituents, or they may be purposely introduced because of their desirable influence of physical properties.

Aluminum in brass. — In experiments recorded in a book on "Alloys," by Sexton,* page 108, aluminum, 0 to 5 per cent, was added to brass with 60 per cent copper, and to brass with 70 per cent copper. The copper content was kept constant and the 100 per cent was made up by aluminum and zinc. In other words, aluminum displaced zinc up to 5 per cent. In both cases the result was an increase in tensile strength and a reduction in ductility. Since this same result could be accomplished more cheaply by increasing the proportion of zinc, the use of aluminum would seem hardly to be justified. Of course a small amount of aluminum would be useful as a flux in melting and casting, reducing copper oxide and removing gas that would produce porosity; but this aluminum would not appear in the alloy.

Manganese in brass. — When manganese, 0 to 7 per cent, displaces zinc in brass with 60 per cent copper † the effect is slight increase in strength and slight decrease in ductility. Also there is the same result when manganese, 0 to 10 per cent, displaces zinc in brass with 70 per cent copper. The result here, as in the case of aluminum, would not seem to justify the use of manganese. The manganese, like the aluminum, may be used for a flux.

Iron in brass. — Iron is often present in brass in very small amount, derived from iron tools used during melting

* Scientific Publishing Company, Manchester.

† "Alloys," by Sexton, p. 117.

and cooling. Iron is also introduced into brass up to a little more than 1 per cent giving a ternary alloy called "delta metal" which is said to have advantages of strength and ductility. The iron is first alloyed with the zinc, and this alloy is then melted with copper.

Arsenic and **antimony** in very small quantities are often present in brass, being brought as impurities in the copper; both are very undesirable, making the brass hard and brittle. Antimony is especially bad in brass that is to be rolled or drawn since it produces "cold-shortness"; it should not exceed 0.01 per cent. The ill-effect of arsenic is less, but it should not exceed 0.05 per cent.

Oxygen in brass. — The copper constituent of brass oxidizes very readily during melting and casting, and copper oxide formed makes the brass weak and brittle. As stated above the copper oxide can be reduced by use of aluminum or manganese used as a flux; phosphorus also is often used very effectively for this purpose.

Bronzes or copper-tin alloys. — Fig. 33 gives the equilibrium diagram * for the copper-tin alloys, with the tensile strength and ductility diagram in the same relation as for copper-zinc in Fig. 32. The strength and ductility curves show that useful alloys for stress-members are confined to the range copper 100 per cent to copper about 85 per cent.

The equilibrium diagram shows that several solid solutions and one chemical compound are formed in the series; the α solution seems to possess fair strength and ductility and hence shock resistance; the β solution obviously is not stable at air temperature, and the presence of the free δ solution is fatal to ductility. With ordinary

* From a paper "The Constitution of the Copper-Tin Alloys," by E. S. Shepherd and E. Blough, *Journal of Physical Chemistry*, Vol. X, p. 630.

rate of cooling β crystals in small amount are retained with copper under 91 per cent and a larger amount may be held by quenching.

The copper-tin alloy that gives the best combination of strength and ductility, and hence of shock resistance, is copper 90, tin 10, and this alloy is most commonly used in machines.

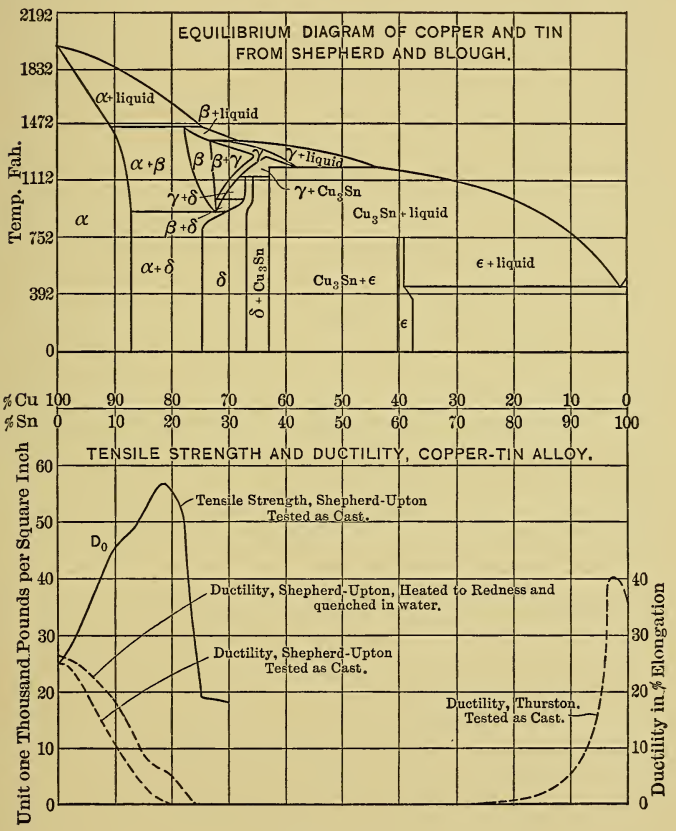


FIG. 33.

Heat treatment of bronzes. — Shepherd and Upton made a careful series of tests of the physical qualities of the copper-tin alloys.* The strength and ductility curves of Fig. 33 are taken from their report. Their work also included a study of heat treatment of these alloys. The heat treatment methods were as follows:

A. — Heated to low-red, water quenched.

B. — Held one week at 1000° F., water quenched.

C. — Tested as cast.

D. — Held one week at 752° F., furnace cooled.

The lettered curves of Fig. 34 show the effect of these methods of heat treatment upon the ultimate strength of bronzes from copper 100 per cent to copper 65 per cent. In Fig. 35 the curves show the corresponding effects upon ductility. Methods B and D are of scientific interest, but only methods A and C can be practically applied. Curves *A* and *C*, Fig. 34, show that heating castings to redness and quenching has little effect on strength through the range copper 100 per cent to 87 per cent; but that from copper 87 per cent to 78 per cent, the heat treatment causes a distinct increase in strength. Referring to the equilibrium diagram Fig. 33 shows that alloys in the α field are unaffected by quenching, whereas raising the alloys into the $\alpha + \beta$ field and quenching through the $\alpha + \delta$ field increases strength. This result is probably due to control of proportions of α, β and δ.

Fig. 35 shows that quenching increases ductility throughout the entire range copper 100 per cent to 77 per cent. This result is probably due to the holding of fine grain by quick cooling.

* See *Journal of Physical Chemistry*, Vol. IX, No. 6, p. 441, June, 1905.

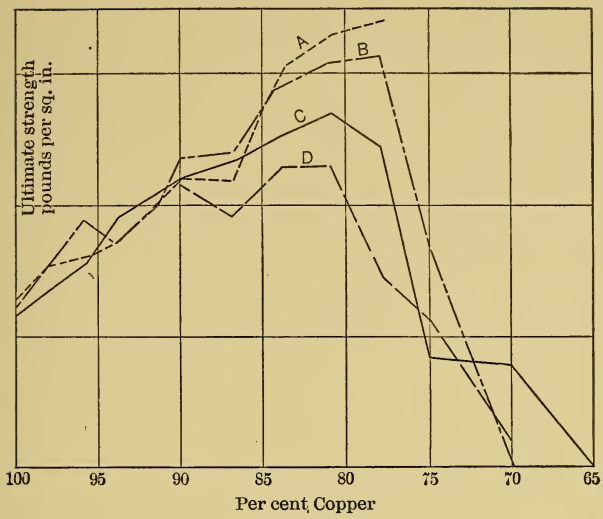


FIG. 34.

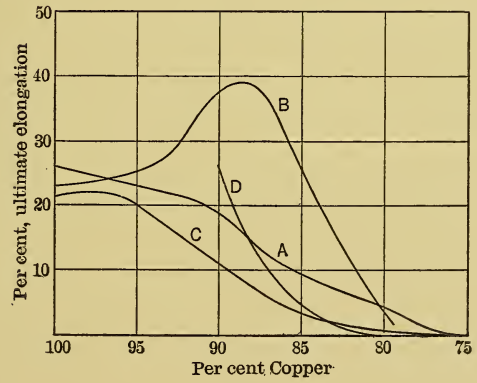


FIG. 35.

A. — Heated to low-red, water quenched.
B. — Held one week at 1000° F., water quenched.
C. — Tested as cast.
D. — Held one week at 752° F., furnace cooled.

M. Guillet's conclusions * from his experiments on heat treatment of bronzes are as follows:

1. In the case of alloys containing over 92 per cent of copper, the tenacity is slightly increased by quenching between 752° F. and 1112° F., and the elongation is similarly affected.

2. In the case of alloys containing less than 92 per cent of copper the tenacity and the elongation increase decidedly as soon as the quenching temperature exceeds 932° F.

3. Maximum strength is reached, whatever the composition of the alloy, at a quenching temperature of about 1112° F.

4. Maximum elongation is reached by quenching from temperatures which vary with the composition of the alloy. With 91 per cent copper, maximum elongation corresponds to a quenching temperature of 1472° F., while with 79 per cent, the maximum elongation corresponds to a quenching temperature of 1112° F.

5. The difference between the tenacity of the cast alloy and that of the metal quenched at the most desirable temperature is the greater the less the percentage of copper.

Copper-aluminum alloys. — A very careful investigation of copper-aluminum alloys was made by the Alloys Research Committee of the British Institution of Mechanical Engineers, reported in the *Proceedings*, 1907. In the summary of conclusions it is stated that the limit of industrially serviceable alloys must be placed at 11 per cent of aluminum.

Fig. 36 gives an equilibrium diagram † of copper-

* See "Alloys" by A. H. Sexton, p. 136.

† See The Constitution of the Aluminum Bronzes, by B. E. Curry, *Journal of Physical Chemistry*, Vol. XI, p. 425.

aluminum and corresponding strength and ductility curves from the A.R.C. report. The aluminum limit in the diagrams is 15 per cent.

In the lower diagram:

Full line *A* gives strength of sand castings;
Full line *B* gives strength of chill castings;
Full line *C* gives strength of rolled bars;
Broken line *A* gives elongation in 2 inches of sand castings;
Broken line *B* gives elongation in 2 inches of chill castings;
Broken line *C* gives elongation in 2 inches of rolled bars.

The very high values of elongation may be accounted for in part by the fact that the original length of tested portion was 2 inches. The useful range may be divided into two parts: aluminum 0 per cent to 8 per cent, and aluminum 8 to 11 per cent. In the first division, increase in aluminum content causes steady increase in tensile strength, and, up to about $7\frac{1}{2}$ per cent aluminum, steady increase in ductility. In the second division, the strength rises more steeply while the ductility falls steeply to a value corresponding to great brittleness at 11 per cent aluminum.

The first division gives strong, very ductile, shock-resistant alloys.

The second division gives more desirable alloys where ductility should be sacrificed to gain greater strength.

Comparison of full and broken curves *A* and *B* shows that chill casting does not give any strength or ductility advantage over sand casting up to 8 per cent aluminum, but that between 8 and 11 per cent aluminum chill casting increases both strength and ductility. Curves *C*

show that rolling increases both strength and ductility in the first division, but that in the second division rolling gives about the same results as chill casting.

Two kinds of heat treatment were applied to the sand

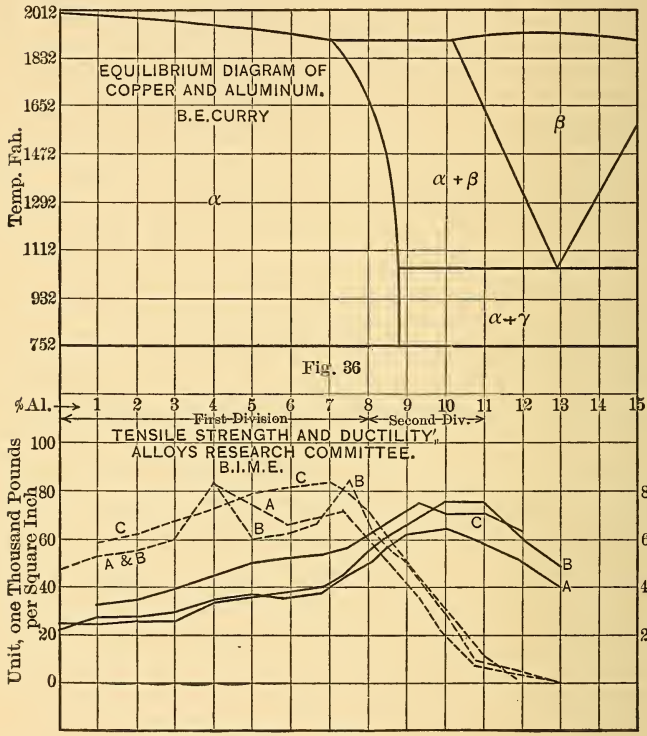


FIG. 36.

castings, the chill castings and the rolled bars; they were heated to about 1472° F. and cooled slowly; they were heated to about 1472° F. and quenched in water.

Neither slow cooling nor quenching from 1472° F. seems

to produce very great change in strength or ductility of sand castings.

In case of chilled castings slow cooling from 1472° F. has little effect up to 8 per cent alloys, but from 8 per cent aluminum to 11 per cent both strength and ductility seem to be somewhat reduced. Quenching from 1472° F. seems to have practically no effect upon strength and ductility.

Rolled bars cooled slowly from 1472° F. show increasing decrease in strength throughout the entire range, and increase in ductility until near the 11 per cent limit. The effect of quenching rolled bars from 1472° F. seems to be to decrease strength and increase ductility up to 8 per cent aluminum and from 8 to 11 per cent aluminum to increase strength and to decrease ductility.

A comparative study of Figs. 32, 33 and 36 shows that there is great similarity among the copper-zinc, the copper-tin and the copper-aluminum alloys. In each case there are two useful ranges; one of medium strength and high ductility, and hence of high shock resistance, another of rapidly increasing strength and rapidly decreasing ductility.

The first range in each case corresponds nearly to the field of α solution of the equilibrium diagram, while the second range corresponds to the introduction of some other solution of the constituents which in increasing proportion rapidly reduces the alloys to brittleness and uselessness.

Kalchoids. — Dr. Thurston made a very full series of experiments on the ternary alloys of copper, tin and zinc, which he called kalchoids. He represented the whole field of possible combinations of the three metals by an equilateral triangular area. Many points at equal distances from each other were located in this area, and each represented an alloy with certain proportions of the three

constituents. Alloys were made corresponding to each point, and tested. At each point was erected a piece of wire whose height represented the strength of the alloy represented by the point. Plastic material was then filled in between the wires, and its surface was molded so that the points of the wire just showed through. This surface represented topographically the varying strength of all possible mixtures of copper, tin and zinc, and the alloy of maximum strength was thereby located. (See Thurston's "Textbook of the Materials of Construction," page 466.)

Phosphor bronze. — When any alloy containing a high percentage of copper is melted in contact with the air, there is a strong tendency to form copper oxide, the affinity of copper for oxygen being exceedingly strong. If the cooled alloy contains copper oxide, it is weak and brittle, just as iron containing iron oxide is weak and brittle. Copper alloys are usually melted with charcoal upon the surface to prevent oxidation, but the prevention is not complete. If phosphorus is added to the alloy just before pouring, the copper oxide is reduced and phosphoric acid is formed, i.e., the alloy is purified by the fluxing action of the phosphorus. This increases both the strength and ductility of the alloy. If an excess of phosphorus is added, part of it may combine with the alloy and increase its strength and ductility, but the proportion of phosphorus should not exceed 0.1 per cent or brittleness results; it is probable that the chief value of its presence is to prevent the formation of oxide of copper during remelting.

Manganese bronze is made either by fusing together (*a*) copper and black oxide of manganese, or (*b*) copper or bronze and ferromanganese. In the first case the product is an alloy of copper, manganese and iron, and

in the second, an alloy of copper, tin, manganese and iron. Some of the manganese is effective in removing, or preventing the formation of, oxide of copper, while the remainder combines with the copper or bronze to give it very greatly increased strength, ductility and toughness. A manganese bronze, copper 83.45 per cent, manganese, 13.48 per cent, iron, 1.24 per cent, has a strength and ductility equal to that of open-hearth steel with 0.2 per cent carbon. It is much used for marine propeller-wheels because it does not corrode easily.

All of the useful copper alloys are more or less forgeable. "Muntz metal," copper 60, zinc 40, is rolled at a red heat into plates for sheathing ships, and into forms for bolts and other fastenings. It is stronger, cheaper and more durable than pure copper. The working of Muntz metal at red heat is possible because it is in the β field* at that temperature, and the β solution is ductile. On cooling, however, it enters the $\alpha + \gamma$ field losing ductility. The effect of cold working upon the copper alloys is similar to that upon iron and steel; viz., the strength and hardness are increased and the ductility is decreased; hence the material is more brittle. This will be clear on comparing hard-drawn brass wire with the same wire after annealing.

Brass and bronze of different composition are used for journal boxes, but modern practice favors a box of cast iron, brass or bronze, with a lining of softer metal, usually a white alloy.

One group of these white alloys is made up of tin with small proportions of copper or antimony or both to produce strength and hardness.

Thus "Babbitt metal" consists of tin about 89 per cent, copper 2 to 4 per cent and antimony about 7.5 to

* See Fig. 32.

9 per cent. This is an excellent bearing alloy, but it is expensive.

Another group consists of lead hardened with antimony. The antimony varies from 10 per cent to 20 per cent and sometimes a small amount of tin is added. This alloy is comparatively inexpensive.

CHAPTER XII

SELECTION OF MATERIALS FOR MACHINES

The more important materials used in machine construction may be brought together as follows:

1. High-speed steel.
2. High-carbon steel.
3. Mild steel, produced by the Bessemer or open-hearth process.
4. Special structural steel.
5. Wrought iron.
6. Cast iron.
7. Malleableized cast iron.
8. Steel castings.
9. Brass or bronze.
10. White metal. This name includes all of the white alloys used for lining journal-boxes, etc.

1. High-speed steel is valuable because of its hardness and toughness which fit it for cutting tools for metals, and especially because it retains these qualities when raised to red heat. This makes very high cutting speed possible with corresponding increase in output of metal cutting machines. This steel is very expensive because of its constituents, its manufacture and its heat treatment, but the expense is amply justified by the results.

2. High-carbon steel is still used for a wide range of cutting tools and it is valuable because of its quality of hardening and tempering. It is also useful for stress members where great strength combined with medium

ductility is of prime importance; also for springs because of its wide natural or artificial elastic range.

3. Mild steel by reason of its medium strength, high ductility and low price is used in structures and machines for all except special service.

4. Special structural steels containing nickel, chromium, vanadium, etc., are useful because their high strength, ductility and shock resistance fit them for light shock-enduring structures like motor cars and aeroplanes, as well as for great shock resistance in projectiles and armor plates.

5. Wrought iron has the advantage over mild steel that it forges much more easily, probably because of its slag content, and hence it is used quite extensively for hand-forging. It is also claimed that it is less subject to destruction by corrosion and hence it still competes with steel for pipes, boiler tubes and similar service.

6. Cast iron is almost universally used for forms that must be shaped by casting, especially where great weight is unobjectionable or where great weight is desirable, as in fly-wheels, machine beds or frames. When cast forms require both strength and lightness, cast iron gives place to other material.

7. Malleable iron is used for cast forms that require great shock-resistance — for purposes for which brittle cast iron is unsafe.

8. Steel castings meet the same need as malleable cast iron, but the process for production and the nature of the material adapts them to much larger machine members.

9. The copper alloys have no advantage over mild steel in strength, ductility and shock resistance, and hence, since the cost is very much greater there must be some other advantage to lead to their selection for machine

parts. These alloys are much safer against oxidation than steel and hence are used for condenser tubes, often for feed pipes, for valves of many kinds and for many parts of mechanisms subject to corrosion. Moreover these alloys have good anti-friction qualities and are used for wearing surfaces.

10. The white alloys are chiefly useful for wearing surfaces. The surfaces of machine parts that move over each other under pressure are normally separated by a film of lubricating material. But under exceptional conditions the metallic surfaces themselves may come into contact; when this occurs the danger of roughening or destroying the surfaces depends somewhat upon the excellence of the surface and kind of material.

A material may be well adapted for wearing surfaces because of (*a*) hardness, (*b*) slipperiness, (*c*) homogeneousness or (*d*) because it is partly composed of lubricating material.

Thus, (*a*) hardened tool-steel is difficult to roughen because of its hardness; (*b*) white metal, though soft, is difficult to roughen, because the roughening agent slides over the slippery surface; (*c*) mild steel would have less tendency to roughen an engaging surface than wrought iron, because the former has a homogeneous surface, while the latter carries streaks of gritty cinder; (*d*) cast iron tends to wear smooth rather than rough, because it contains graphitic carbon, a lubricating material.

The ideal for rotating surfaces would be a hardened, accurately ground, crucible-steel journal, with its bearing lined with high-grade white metal. But here the question of cost enters, for the cost of the journal specified includes high first cost for the crucible steel, the cost for hardening, and a cost incident upon the loss of expensive parts through cracking in the process of hardening. In

addition to this, an expensive plant is required for the hardening of large journals.

In standard practice mild steel journals are used with bearings lined with white metal; but there are often conditions that lead to the use of other materials.

Sliding surfaces in machines are often formed upon cast-iron members, and the engaging surface is also of cast iron. The frictional loss may be reduced by giving one surface a white-metal covering.

To illustrate the selection of materials for machine parts, a few typical examples will be discussed.

The **cylinder of a steam-engine,** with its ports and its connected steam-chest, is of such complicated form that it is almost impossible to shape it by forging; or if the forging were possible, it would be too expensive. The possible materials which may be used for such a cylinder are, therefore, only those which are shaped by casting. Brass and bronze would have no advantage over cast iron, and would cost about ten times as much. They are, therefore, out of the question. Steel casting might be used, but the first cost of the material would be somewhat greater, and the cost of working in the machine-shop would be very much greater. Additional strength and resilience would be gained, but this is unnecessary, as cylinders, even for very high pressures, can be made of cast iron, amply strong and resilient, and yet not objectionably thick. Moreover, cast iron is one of the very best possible materials for the wearing surfaces of the cylinder and valve-seat. Cylinders subjected to excessively high pressure, as 300 to 700 pounds per square inch, should perhaps be made of steel castings, as, for instance, the cylinders of pumps for pipe-lines, or for supplying hydraulic machinery.

The **piston-rod of a steam-engine** is of mild steel.

The entire force of the steam acting on the piston must be transmitted to the cross-head through the piston-rod; also, since the effective area of the piston on the crank side equals the total area of the piston less the area of the rod, and since the effective area needs to be as large as possible, the rod should be as small as possible. There is always the liability to shocks, and, therefore, since the rod must be small and at the same time strong, and must also be capable of resisting shocks, a material of high unit strength and of high resilience is required. Soft steel is the material which combines these qualities.

A **steam-engine cross-head pin** is always made much larger than is necessary to safely resist shearing, or springing by flexure, to insure the maintenance of lubrication; cast iron might serve, then, as far as strength and stiffness are concerned, and in fact is sometimes used. But there is another important consideration: because of the vibratory motion of the connecting-rod on the pin, there is a tendency to wear the pin oval, and when the boxes are "keyed up," they will bind when the rod is in its position of greatest angularity, if it is properly adjusted when the rod is on the center line of the engine. Because of this it is desirable to reduce the wear to a minimum, and this points to the selection of a hard material. Hardened tool-steel might be used, but it is more expensive than soft steel or wrought iron, and there is the danger of hidden cracks, resulting from the hardening, which may cause accident. If soft steel is case-hardened, it will combine a hard surface to resist wear with a soft resilient core, free from the danger of cracks. Wrought iron case-hardened might be used, but wrought iron, because of the method of manufacture, has streaks of cinder in its surface, and lacks the homogeneity of the steel, and is therefore harder to make, and to keep truly cylindrical. It

therefore should not be used where perfection of bearing and accuracy of movement are essential.

The **connecting-rod of a steam-engine** is subjected to the alternate tension and compression resulting from the pressure on the piston, and also to a flexure stress due to its vibratory motion. These stresses are very severe, and there is also liability to shock. The material of the rod should be strong and resilient, and soft steel would naturally be selected, since it is a forgeable material. But there is another important consideration; the rod is to be finished, and wrought iron is much more cheaply worked in the machine-shop than soft steel, and the expense of forging is also much less. The lack of homogeneity is of no importance, as no part of the rod is a bearing-surface. Many connecting-rods are made of steel casting, and finished by painting. This makes a cheaper rod, but there is always the danger of hidden defects, like cracks, due to the excessive shrinkage, or blow holes, which may weaken the rod enough to cause accident.

The **cross-head of a steam-engine** is composed of two parts: (*a*) that which serves to transmit the pressure from the piston-rod to the cross-head pin, and (*b*) that which engages with the guide to produce rectilinear motion. The stresses on (*a*) are severe, and there is liability to severe shock; hence it must be of strong resilient material; the stresses on (*b*), however, are less, but it must be of material which will run well with the guide, which is usually of cast iron, being a part of the engine-bed. The cross-head may be made of materials as follows: (*a*) may be made of forged wrought iron or soft steel, and (*b*) may be of cast iron bolted to (*a*), or the whole cross-head may be made of cast iron, the part (*a*) being made enough larger than before to be sufficiently strong;

or the cross-head may be made a casting of steel and a "shoe" or "gib" of cast iron or brass may be added to provide a proper surface to run in contact with the guide.

The **crank-pin of a steam-engine** is subjected to the same stress as the cross-head pin, and the velocity of rubbing surface is very much greater, hence the tendency to wear is greater. But the tendency to wear "out of round" is less and therefore there is less interference with the correct adjustment of the boxes; hence there is less reason for keeping the wear a minimum; a good journal surface is necessary, and soft steel is used without case-hardening.

The **main shaft of a steam-engine** needs to be strong and rigid to resist a combination of severe stresses, i.e., the torsional and transverse stress from the connecting-rod, and the transverse stress due to the weight of the fly-wheel, and the belt tension. It must also afford a good journal surface, and for these reasons it is made of soft steel.

The function of the **fly-wheel** of a steam-engine is to adapt a varying effort to a constant resistance, and it does this by absorbing and giving out energy periodically by virtue of its inertia, which is proportional to its weight; it therefore needs, above all things, to be heavy; it also needs to be able to resist the bursting tendency of the centrifugal force due to its rotation. The most suitable material therefore is that which gives the greatest weight in the required form, with the required strength, for the least money; and cast iron best fulfills these requirements.

An engine bed or frame, when it is in one piece, is of cast iron, and the reasons are obvious: its form is complex, and could only be produced by casting; weight is not objectionable, but rather an advantage, since it

absorbs vibrations; cast iron is amply strong, and affords good wearing surfaces for the cross-head guides. Wrought iron is used for engine-beds, where vibrations are less important, as in the locomotive, and where lightness and compactness are very desirable, as in some marine engines. The beds of some large roll-train and blowing engines are built up of wrought and cast iron.

The **journal-bearings,** or boxes for the cross-head pin, the crank-pin and the journals of the main shaft are now usually made of cast iron or brass, with a babbitt-metal lining, because good babbitt metal (tin 80, copper 10, antimony 10) is found to be a better bearing metal than brass, i.e., it runs with less tendency to heat; and in the case of the cutting out of the surface, the babbitt-lined box is far more quickly and cheaply renewed than the solid brass box.

The **eccentric** and its **strap** are almost invariably made of cast iron, because they are forms which are forged with difficulty, and the cast iron affords ample strength and excellent wearing surfaces. The **eccentric-rod,** on the other hand, would be cumbersome and ugly in appearance if it were made of cast iron and given sufficient strength. It is a form which may be easily either forged or cast, and is made of forged wrought iron or steel, or of cast steel, or of malleableized cast iron. **Rocker-arms,** also, when they are used, require to be of a resilient material, and when of simple form may be forged of wrought iron or steel, and when of more complex form may be of malleableized cast iron, or steel casting. The **valve** is usually of somewhat complex form, and needs to wear well with the cast-iron valve-seat, and is almost invariably of cast iron.

Considerations similar to those above apply to the selection of proper material for the parts of **machine**

tools. Thus, in the case of a lathe, the bed, legs, head and tail-stock, cone, gears, etc., are of cast iron, because they are all forms which are most cheaply and satisfactorily produced by casting, and the cast iron affords the required strength and stiffness, and satisfactory wearing surface, where they are required. Such parts as lead-screws, feed-rods and other parts which are subjected to considerable stress, and have great length relatively to their lateral dimensions, are made necessarily of wrought iron or steel. Many of these parts may be finished in the machine-shop directly from merchant-bar stock, thus saving expense for forging.

The material for the parts of planing, milling, and drilling machines are determined from exactly similar considerations.

Spindles, however, require special attention. In lathes, milling and grinding machines the accuracy of the work produced depends largely upon the accuracy of the spindle.

The vital point therefore is to maintain this accuracy, i.e., to prevent wear as far as possible. It would seem then that hardened tool-steel would be the best material. But since only a very small amount of stock can be removed by the grinding machine after the piece is hardened, the spindle must be roughed out very nearly to size before it is hardened; this involves a very considerable expense, and there is danger that it may crack in hardening, or spring so as not to hold up to finish, in which case the loss is great, and it is found that the risk cannot be taken. The next best thing is to specify machinery steel high in carbon (say 0.4 per cent), and to use this harder material for the spindle without hardening. In milling-machines and in some lathes the main spindle-box is solid, of tool-steel, hardened and ground (the risk of loss being

less in this case), and the spindle as before is of 0.4 per cent carbon machinery steel. The wear is thus greatly reduced, and the possibility of wear after long use is provided against by making the bearing taper, and providing end adjustment. The spindles of very large lathes are sometimes made of cast iron, because forged material would be too expensive. The wear is reduced by making the journals very large.

In the steam or hydraulic **riveter** the main frame which supports the cylinder, and carries the guide for the moving die, may be of any reasonable size, and therefore can be made strong enough to resist even the very great forces applied to it, if the material used is cast iron. But the "stake," the member which carries the stationary die, must resist exactly the same forces as the main frame, and must also be small enough so that small boiler-shells, and even flues, can be lowered over it to be riveted. The "stake" is therefore of forged wrought iron or steel, or else a steel casting.

Suppose that in a machine there is need of a **gear** and **pinion** whose velocity ratio is 8 to 1, and that the force transmitted is large. A tooth of the pinion comes into action eight times as often as a tooth of the gear, and therefore would wear out in one-eighth of the time if both were of the same material; then, too, the form of the pinion-tooth in most systems of gearing is such that it is much weaker than the gear-tooth. The material for the pinion needs, therefore, not only to be stronger, but also better able to resist wear. The gear is made of cast iron; if the teeth are cut, the pinion may be made of forged steel; if the teeth are cast and used without "tooling," the pinion may be made a steel casting.

Material for Springs. — Springs are useful as machine parts because of their capacity for yielding without taking

permanent set. The yielding, therefore, must occur with stresses that do not exceed the elastic limit. Clearly, then, the material with large elastic range, i.e., with high elastic limit, is the best material for spring machine-members.

Crucible-steel has the highest normal elastic limit, and this limit is raised by hardening and tempering. This is the most commonly used material. Untreated mild steel may also be used, but with given stress the spring must have greater weight than if higher carbon steel were used. The steel may have its normal elastic limit artificially raised by cold working (cold rolling or wire-drawing), and this improves it as a spring material. Brass, bronze and other alloys are used for springs, but usually in the form of hard-drawn wire with an artificial elastic limit.

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